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MAGNESIUM CASTING TECHNOLOGY

MAGNESIUM CASTING TECHNOLOGY

by

A. W. BRACE
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PREFACE

THE PREMATURE DEATH of Frank A. Allen on 18th January, 1950 robbed the light alloy foundry industry of one of its greatest enthusiasts in the field of magnesium founding. His own original and stimulating contribution was not inconsiderable and it was unfortunate that it was cut short at what might have been his most creative period.

Amongst the papers that he left was an incomplete manuscript for a short monograph on magnesium casting technology which was being prepared for early publication. Owing to various misadventures some time elapsed before it reached the writer.

Its present publication under joint authorship was undertaken as a personal tribute from one who worked with him for many years and valued his friendship, kindliness and encouragement which were so characteristic. The basic material for the book was provided by the manuscript mentioned but much revision and addition was necessary and the final form must remain solely the responsibility of the writer.

It is hoped that this volume will help to provide founders with an understanding of the basic principles of magnesium founding under one cover, instead of the widely scattered information contained in numerous published and unpublished papers as at present. An attempt has been made to present objectively both British and American practice against a background of the more basic chemical and physical properties of the metal.

If this book should encourage more foundries to undertake castings in this metal, which has properties likely to be of increasing interest to engineers, then it will have more than fulfilled its purpose.

A. W. BRACE, A.I.M., C.G.I.A.

Banbury, Oxon.
1955.

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A.W.B.

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CHAPTER 1

Introduction

THE SUCCESSFUL PRODUCTION of magnesium alloy castings depends upon the careful observance of certain well-established principles. It is true that specialized foundry technique is required, but this is because of particular chemical and physical properties of the metal; indeed, these characteristics must be understood for a complete understanding of magnesium practice. The initiate to the craft of ultra-light alloy founding should, therefore, acquire a knowledge of the fundamentals of magnesium chemistry, physics, and metallurgy. In this way he will understand the problems that faced the pioneers and see how their difficulties were overcome, how the technique evolved and, moreover, how the technique is still developing. The industry is young enough, in fact, for the novice of today to become the innovator of tomorrow.

With this approach to the subject, it will soon be accepted that the unique requirements of magnesium technology make sense—even common sense—because they are logically based upon unalterable properties of the metal. Such complete understanding will find culmination in efficient processes and successful production.

The above considerations indicate the plan of this book, which, built on the plan of demonstrating the theory underlying production operations, further gives stage by stage a full account of practical working details. The science and art of magnesium alloy founding will be treated in elementary, yet, it is hoped, adequate terms in this introduction. Each technical aspect of the art will then be dealt with in complete detail in subsequent chapters, the first part of each being reserved for discussion of the theory on which the practice is based.

Chemical Properties

There are, or were, two well-known uses of magnesium that unfortunately convey a wrong impression with regard to inflammability. At one time magnesium was only known to the general public as powder or ribbon, used by photographers and conjurers to produce a brilliant flash of light. More recently the magnesium incendiary bomb has spectacularly, and often disastrously, confirmed the popular idea of extreme inflammability. This destructive use of the metal has made sensible propaganda the more urgent. Both the photographer's ribbon and the fire bomb are special cases and must not be taken as indicating the properties to be expected in engineering applications of magnesium alloys. Magnesium powder and ribbon burn fairly easily because in a free atmosphere the temperature may be quickly raised to a temperature well above that used for normal melting operations in the foundry. Incendiary bombs which consist essentially of a magnesium alloy container, burn vigorously because the contents evolve oxygen and create intense heat sufficient to melt the alloy container and then to ignite it. Normally the ignition of magnesium alloy depends upon the mass. Fine powder burns readily; machine-shop swarf with greater difficulty—machine-shop swarf fires are often extinguished by the addition of more swarf—and components of normal masses as used in engineering cannot be ignited by any normal accidental method.

An experiment was once made of burning petrol in a box fabricated from magnesium alloy sheet which had, of course, a much thinner section than a casting. The petrol burned away and the magnesium alloy container remained completely unharmed.

Elementary chemistry textbooks, as a general rule, describe the reaction of substances either at normal temperatures or at the slightly elevated one of boiling water. The foundryman, on the other hand, must concern himself with the properties of metals at and above their melting points, so that if oxidation occurs by the action of water at boiling point, the reaction at, say a temperature of 700°C. (1292°F.) is likely to give rise to practical difficulties. Such conditions do, of course, obtain when molten metal enters a mould made of sand containing 3 or 4 per cent of moisture.

The physical form of the oxide produced is an important consideration with regard to molten metal treatment. If the film is continuous the oxide film acts protectively, while if the oxide is granular and porous, little resistance to the oxidizing action is offered, and oxidation will be progressive. The difference between the surface behaviour of molten aluminium alloy and molten magnesium alloy strikingly illustrates this point. The surface of molten aluminium consists of a tough thin film which acts as a protective envelope. In contrast, the surface of molten magnesium alloy suffers from almost continuous degradation, for innumerable sparks appear at points which become centres of oxide formation until the total area is covered by bulky porous white magnesium oxide. This cover offers no protection and oxidation continues beneath it. It is vitally important, therefore, that oxidation of molten magnesium alloys shall be prevented so that the melting loss does not become excessive.

The difference between the properties of molten aluminium and molten magnesium may be used again to demonstrate another point of practical importance. Every aluminium founder is aware that his molten metal is prone to absorb gas to a marked degree. Hydrogen gas is absorbed from furnace gases, or from decomposition of corrosion products held on the ingot surfaces, and unless this gas is removed from the metal before casting, it will reappear on solidification giving the well-known defect of pin-hole porosity. In a practical sense, magnesium does not absorb gas, at least not with the same result obtained in aluminium alloys. There is a typical defect associated with gas absorption which may arise, and this is known as micro-porosity, but it does not give rise to the troublesome pin-holing found in aluminium castings. The whole subject of gas pick-up in molten magnesium and consequent defects and cures will be treated in detail in a later chapter.

Foundry Characteristics

Pure magnesium melts at a temperature of about 650°C. (1202°F.) and, as one would expect, the alloys commence to melt at a lower temperature. The normal casting alloys on cooling commence to become solid at a temperature of about 580°C. (1076°F.) and are usually completely solid around 400°C. (776°F.). There is thus an extended freezing range, during which the metal is neither solid nor liquid but is a mixture of the two states. During this period, solidification proceeds continuously, and contraction cavities or shrinkage tend to be formed. Large risers or feeders, remaining fluid long enough to make good such holes as they appear, are therefore necessary as a general rule.

The fluidity of molten magnesium alloys may be approximately indicated as lying between that of the free-running high silicon-aluminium alloys ('Alpax' type) and the more sluggish complex copper-nickel-magnesium-aluminium ('Y' and 'RR' alloys) series. The usual casting temperatures for magnesium alloys lie in the range 720°–800°C. (1354°F.–1498°F.); in conformity with good casting technique for any metal, the gating and running system should be so designed that the lowest practicable pouring temperature can be used. With special reference to magnesium, however, it must be remembered that the higher the temperature the greater the tendency to burn—an added reason, therefore, why pouring temperatures should be kept as low as possible.

It is, of course, a general rule of non-ferrous founding that the metal must be prevented from overheating during the melting process. The many reasons for this are not far to seek: copper-zinc alloys, for example, tend to suffer from zinc losses if the temperature is allowed to rise unduly; aluminium alloys gather hydrogen, and if the metal is agitated, oxide films, which are difficult to remove, are held in the metal. Magnesium-aluminium alloys, in sharp distinction, actually improve when super-heated materially above the pouring temperature range. Metal so heated in an iron or steel crucible and held for a short period is of finer grain, has better machining properties, and is of higher mechanical strength as a result. The effects due to super-heating may be obtained by simpler means, but because super-heating is an accepted part of magnesium melting technology, it will be discussed in greater detail at a later stage: in addition, the more recent practice giving grain refinement at lower temperatures will also be discussed.

Castings in most of the present foundry alloys can be heat treated with material improvement of mechanical properties. Accurate temperature control is essential but this is not a novel requirement in heat treatment processes for ferrous or non-ferrous alloys in general. Solution treatment, that is at comparatively high temperature, is sometimes performed in a salt bath of fused chromates or more frequently in an air circulating oven fired by oil, gas or electricity.

At the temperature of solution treatment, magnesium alloys have little mechanical strength and care must be taken to prevent distortion. For the same reason, dies for the production of gravity die castings must work quickly and smoothly in order that the act of ejection shall not impress sufficient strain to produce distortion.

The use of X-ray equipment for inspection has been a tool in routine use since the war, and while no doubt most commercial applications will not necessitate so full a use of radiography, its use as a aboratory tool guiding moulding technique in pre-production stages has come to stay. Fortunately, magnesium alloys are easily penetrated by X-rays and modern sets of quite modest power give negatives of high definition. Inspection by fluoroscopy, that is, the method in which an image is thrown on a fluorescent screen, reveals major defects but does not show micro-porosity with any degree of certainty. The subject of inspection will be discussed fully in a later chapter.

A word must be added on a characteristic defect of magnesium alloy castings. The extended freezing range of these alloys has been mentioned—the experienced foundryman anticipates shrinkage cavitation unless he feeds at the correct points. Magnesium alloys, however, tend to suffer from cavitation of a fine form even in these sections which one would normally expect to be perfectly sound. The defect tends to show itself in the form of areas or 'lakes' of fine porosity which are more marked in areas which it is difficult to feed but not confined to them. This type of peculiar cavitation is known as 'micro-shrinkage' or 'micro-porosity'.

Radiographical inspection of light alloy castings for aircraft used during the war has made founders and users 'porosity-conscious', but there are probably many commercial applications for ultra-light castings in which such minor imperfections are not at all important. It is accepted that the perfect casting in any metal has yet to be made; the fact that light alloy foundries in general, and magnesium alloy foundries in particular, were not invariably successful in producing high quality castings subject to strict metallurgical inspection for war-time aircraft use, should not bias the foundryman to think of their production as insuperably difficult; neither should the user avoid entering the commercial field.

CHAPTER 2

Magnesium Casting Alloys

In common with aluminium and many other metals, pure magnesium is too weak to be used commercially without alloying, having an ultimate tensile strength of 6–7 tons/sq. in. as cast. Work by Hume Rothery[1] has shown that for an appreciable strengthening to be produced the added element must form a solid solution with the base metal. Solid solutions cannot be formed to any appreciable extent if the atomic diameter of the added metal differs from that of the solvent metal by more than about 14 per cent, and provided that the crystal structure is not greatly dissimilar and that there is not a strong tendency to form intermetallic compounds.

An examination of the data for such atomic constants shows that aluminium, zirconium, silver, cadmium, lithium, tin, antimony, thallium, lead and bismuth fall within these limits. Several of these however, including antimony, thallium, lead and bismuth can form compounds with magnesium which are both brittle and reactive, so that they can only be added in small amounts if at all. This means that aluminium and cadmium are the main elements suitable foı alloying in more than small amounts. On the other hand, metals such as zinc, cerium, manganese, thorium and calcium, which fall outside of the limits given above can be added in small quantities since they form limited solid solutions. Zinc, although being slightly outside the favourable size range will dissolve in magnesium to an appreciable extent due to favourable chemical factors.

It is well known that alloys such as 'Y' alloy and Duralumin owe their strength to heat treatment. The heat treatment depends upon the fact that the alloying elements are more soluble in the solvent metal at high temperatures than at room temperature. This means that any added constituent must go into solid solution at a high temperature and be retained on quenching but separating out as small, even submicroscopic particles, when exposed to a slightly elevated temperature. Many of the metals listed above can be expected to behave in this manner.

Magnesium-aluminium Alloys

One of the elements having these characteristics, that for many years was the main constituent of magnesium alloys, is aluminium. Under equilibrium conditions[2] 12·6 per cent of aluminium will go into solid solution at 436°C., and this decreases to around 2 per cent at room temperature (see *Fig.* 1). The most common casting alloys contain nominally 8 per cent and 10 per cent of this element together with small additions of zinc and manganese. Several compositions

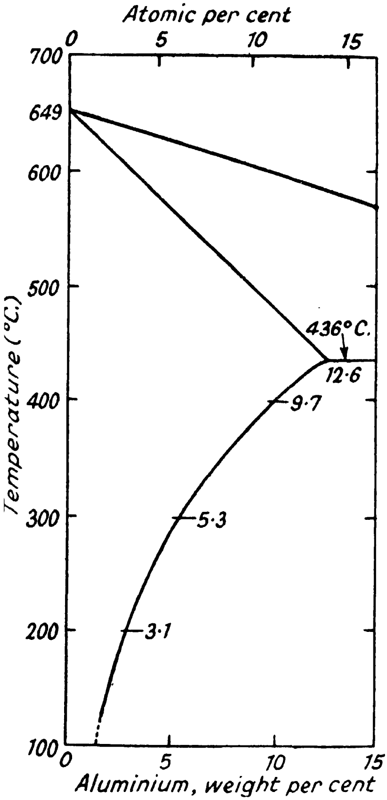


Fig. 1. Magnesium–aluminium equilibrium diagram.

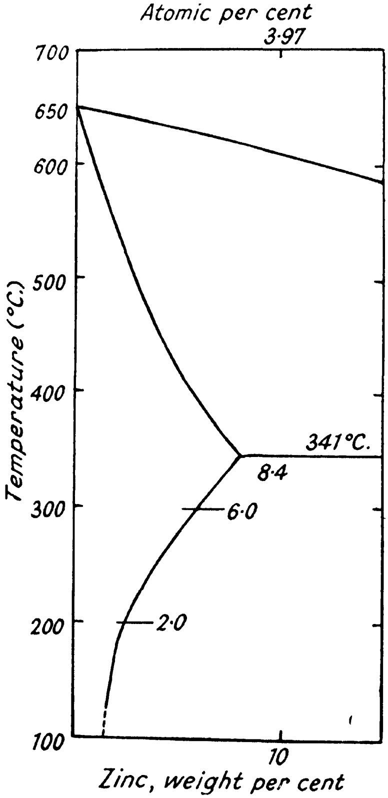


Fig. 2. Magnesium–zinc equilibrium diagram.

are used commercially, there being slightly different compositions favoured in various countries.

In Great Britain the alloy containing nominally 8 per cent aluminium, 0·5 per cent zinc is widely used in either the as-cast or solution heat-treated condition, and both British Standards for Aircraft (L121, L122) and General Engineering (BS. 1277, BS. 1278) cover this material (see Table 1). In the United States the corresponding alloy (AM.80A—Table 2) contains 8 per cent aluminium and virtually no zinc; it is sometimes also produced in the fully heat-treated condition (T6).

The second common alloy is the one containing nominally 10 per cent aluminium, 0·5 per cent zinc, which is produced in Great Britain in the as-cast, solution heat-treated and fully heat-treated conditions. The Aircraft and General Engineering Standards for the material are L123–125 (incl.) and BS. 1273, 1275, 1276. In the United States the corresponding alloy AM100A contains 10 per cent aluminium and only 0·25 per cent zinc, whilst AZ91C contains nominally 9·0 per cent aluminium and the zinc is usually slightly higher (about 0·7 per cent), whilst a similar material but containing 2 per cent zinc (AZ92A) is also used.

British practice tends to favour low zinc contents in these alloys since it is felt they reduce micro-porosity. For this reason an alloy containing 6 per cent aluminium, 3 per cent zinc has fallen into disuse there although it is still produced to some extent in America (AZ63A alloy). Each of these alloys is produced in the three conditions mentioned, but American specifications also include a T5 temper which corresponds to the stress-relief annealed condition used in Great Britain but not normally distinguished from the as-cast condition in terms of mechanical properties.

Manganese has been used as the principal constituent of an alloy covered by the aircraft specification DTD.140B, (MIB) containing nominally 1·7 per cent Mn. Although its mechanical properties are low the corrosion resistance is good and the castings can be satisfactorily welded to sheet or sections of similar composition.

Magnesium-zinc-zirconium Alloys

Zinc is also a major alloying element and the equilibrium diagram[3] (*Fig.* 2) shows that a maximum of 8·4 per cent Zn will go into solid solution at 341°C. decreasing to about 1·7 per cent at room temperature. Alloys containing high percentages of zinc are rather susceptible to a defect known as micro-porosity but at contents of 2 per cent to 6 per cent good casting properties can be obtained with the assistance of the grain refinement produced by zirconium and the strength conferred on room and elevated temperatures by thorium and cerium respectively. Zirconium is said to form a magnesium-zirconium compound[4] in amounts greater than about 0·25 per cent (see *Fig.* 3) and this is believed to provide grain refining nuclei, although around 0·7 per cent of the element is preferred for consistent results.

The first of these, often referred to by its commercial designation

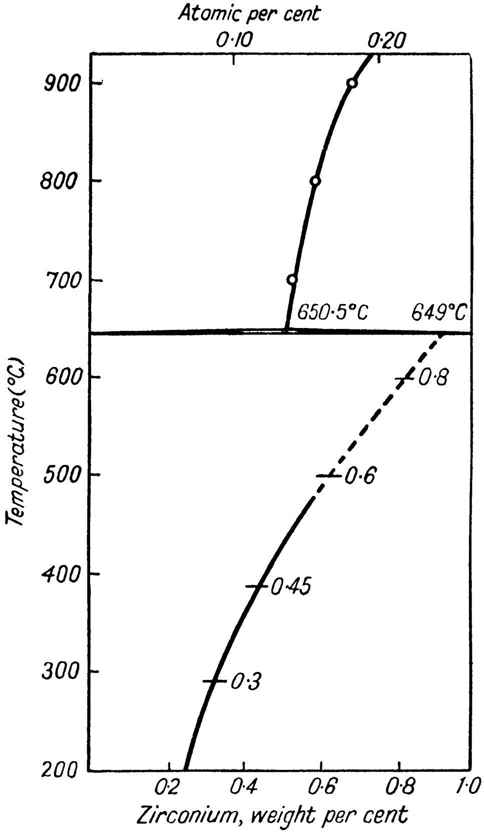


Fig. 3. Magnesium–zirconium equilibrium diagram.

Z5Z, is now covered by DTD.711A and DTD.721A (ZK51A–T5) specifications, covering the as-cast and heat-treated conditions respectively. It consists nominally of 5 per cent zinc and 0·7 per cent zirconium, and gives good tensile properties (see Table 7). Its casting characteristics make it one of the most acceptable magnesium casting alloys and cut up tests on large castings have shown a high degree of consistency in mechanical properties. The microstructure of the heat-treated alloy is shown in *Fig.* 5*a*.

However, subsequent research has shown that the addition of around 1½ per cent of rare earths (DTD.748–RZ5) further improves its casting characteristics with little effect on mechanical properties making it a material that is very free from porosity and easily cast into intricate shapes; it can also be satisfactorily welded since it is not very susceptible to hot cracking.

North American developments have tended towards two alloys, one containing about 4·5 per cent zinc (ZK51A) and the other about 6 per cent zinc (ZK61A). The latter is considered to give rather higher mechanical properties if given a double heat treatment, than those with the lower zinc content.

Alloys Containing Rare Earths

A study of the magnesium-cerium equilibrium diagram[5] (*Fig.* 4) will show that only 1·6 per cent of cerium (as 'mischmetall') will enter into solid solution at 590°C. (the eutectic temperature). The commercial alloys containing this element are two-phase in structure, the second phase consisting of a eutectic of the magnesium solid solution with the compound Mg_9Ce. It is the cerium dissolved in solid solution which primarily confers creep resistance to the material.

In Great Britain two main alloys containing rare earths have been developed for applications where creep resistance is important, one containing nominally 3 per cent cerium and 0·7 per cent Zr (known as MCZ) and the other of the same composition plus 2½ per cent zinc (ZRE1). These alloys are covered by British Aircraft Specifications DTD.728 and DTD.708 respectively. The microstructure of DTD.708 (ZRE1) is shown in *Fig.* 5*b*. American work has tended towards slight differences in composition and heat treatment, it has also been directed towards investigation of the behaviour of alloys low in cerium but based on other rare earth elements such as didymium. Whilst there is some evidence that these latter alloys give slightly superior creep properties up to 200°C. over those of normal cerium content they have not achieved commercial importance, mainly because magnesium-thorium alloys have been developed having outstanding creep properties upwards of 250°C.

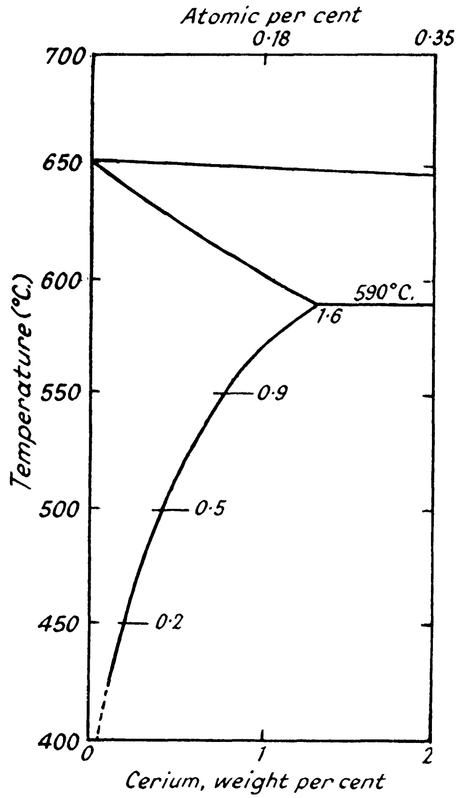
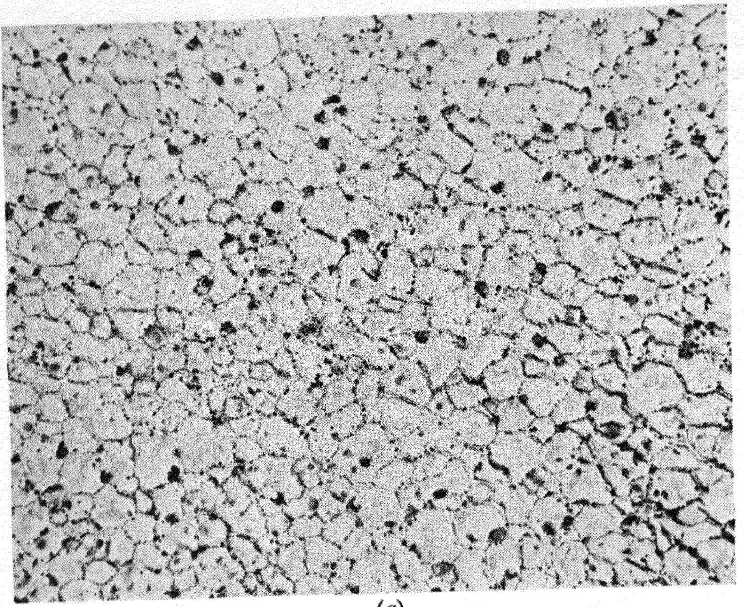


Fig. 4. Magnesium-cerium equilibrium diagram.

The three alloys covered in ASTM B80–53T are EK30A containing 3¼ per cent cerium and about 0·3 per cent zirconium, EK41A with 4 per cent cerium and 0·7 per cent zirconium, and EZ33A of similar composition to ZRE1 alloy. Normally EK30A is fully heat treated whilst EK41A may be similarly treated or given a simple stabilizing treatment which is also the standard heat treatment for EZ33A. There are slight differences in creep properties for these



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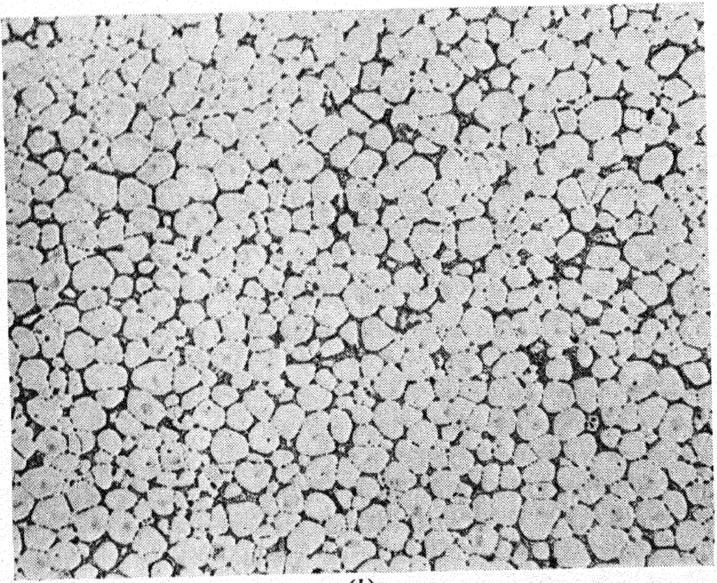

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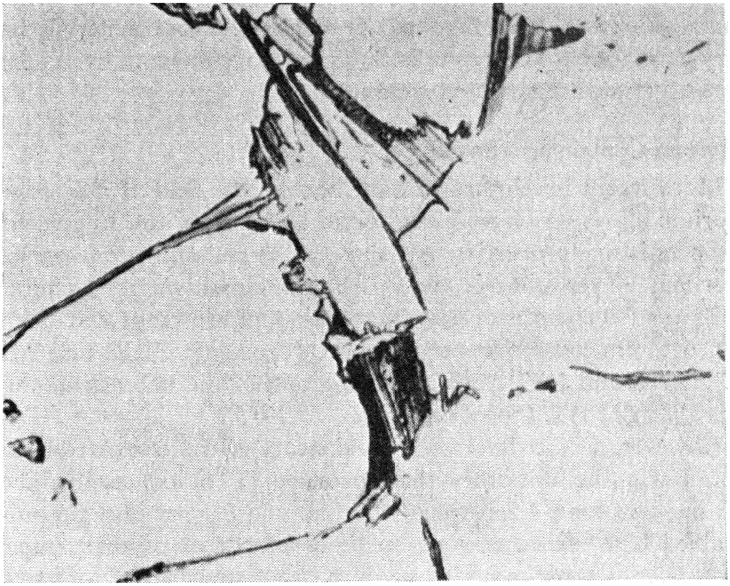


(*c*)

Fig. 5. Microstructures of (*a*) DTD 721a (Z5Z) material after heat treatment (× 150) (*b*) DTD 708 (ZRE 1) as cast (× 150) and (*c*) ZT 1 after heat treatment (× 1000). All samples etched in 3 per cent nital.

(*Magnesium Elektron Ltd.*)

alloys but there is a trend towards acceptance of the two similar compositions to those favoured in England. These materials have very good foundry characteristics, particularly freedom from microporosity; they can be argon arc welded.

Thorium Containing Alloys

More recent developments have been in the field of magnesium-thorium alloys which were considered to be likely also to give good creep resisting properties. An alloy (ZT1) containing 3·0 per cent thorium, 2·2 per cent zinc and 0·7 per cent zirconium has been found to have good creep properties in the temperature range 250°–350°C. and thus are complementary to the earlier alloys ZRE1 and MCZ (DTD.708 and DTD.728). A photograph of the microstructure of this alloy (ZT1) is shown in *Fig. 5c.*

However, a most interesting by-product of the research on these alloys was the discovery that an alloy (TZ6) containing about 5·8 per cent zinc, 1·8 per cent thorium and 0·7 per cent zirconium enabled high tensile strength to be developed at normal temperatures, giving a minimum 0·1 per cent proof stress of 9·5 tons/sq. in. and an ultimate tensile strength of 17 tons/sq. in. with 5·0 per cent elongation. This alloy will obviously be valuable in high strength applications and should find applications outside the field of specialized military requirements. Both thorium containing alloys have similar foundry characteristics to alloys containing rare earths, particularly TZ6, and if welded give very good weld strengths.

The alloys referred to in the foregoing paragraphs obviously provide materials with a range of properties that are attractive to both founder and user, and will provide the basis for a wider usage of magnesium alloy castings. Before closing reference should be made to two other alloying elements which are of some interest. The first of these is lithium 11 per cent of which, if added to magnesium, will produce a body centred cubic crystal structure instead of the normal hexagonal. This produces a material which in sheet form has good forming properties at room temperature. The high price of lithium and the reactivity of these alloys have been unfavourable to their commercial development and it seems doubtful if this position will change in the near future.

On the other hand cadmium is ready soluble in magnesium and useful alloys for extrusion or rolling can be obtained since it forms a

TABLE 1

Chemical Composition and Minimum Mechanical Properties of British Magnesium Casting Alloys

Specifications		Chemical Composition %						Condition	Minimum Mechanical Properties			
Aircraft	Gen. Eng.	Al	Zn	Mn	Rare Earths	Zr	Others		0·1 % proof stress tons/ sq. in.	Ultimate tensile strength tons/ sq. in.	Elongation on 2 in. %	Brinell hardness number *
L121	BS.1277	7·5–8·5	0·3–1·0	0·2–0·4	—	—	—	As cast	4 5*	9·0	2·0	55
L122	BS.1278				—	—	—	Solution treated	4·5*	13·0	6·0	55
L123	BS.1273	9·0–10·5	0·3–1·0	0·2–0·4	—	—	—	As cast	4·5*	8·0	—	55
L124	BS.1276	,,	,,	,,	—	—	—	Solution treated	5·0*	13·0	4·0	55
L125	BS.1275	,,	,,	,,	—	—	—	Fully heat treated	6·5*	13·0	—	80
DTD.140B	BS.1280	—	—	1·5–2·0	—	—	—	As cast	1·5*	6·0	3·0	40
DTD.684	—	7·5–9·0	0·3–1·0	0·15–0·40	—	—	0·015 max.	As cast	4·5*	9·0	2·0	55
DTD.690	—	7·5–9·0	0·3–1·0	0·15–0·40	—	—	0·015 Max.	Solution treated	4·5*	13·0	6·0	55
DTD.708	—	—	0·8–3·0	0·15	2·5–4·0	1·0	—	Aged	5·5*	9·0	3·0	50
DTD.711A	—	—	3·5–5·5	0·15	—	1·0	—	As cast	7·0	13·0	7·0	55
DTD.718	—	—	0·3–0·7	0·15	2·5–4 0	0·4–1 0	—	Aged	5·5*	9·0	3·0	55
DTD.721A	—	—	3·5–5·5	0·15	—	1·0	—	Annealed	8·5	15·0	5·0	65
DTD.728	—	—	—	0·15	2·5–4·0	0 4–1·0	—	Aged	5·5	9·0	3·0	45
DTD.738	—	—	3·5–5·0	0·15	0·75–1·75	0·4–1·0	—	As cast	6·0*	11·0	3·0	50
DTD.748	—	—	3·5–5·0	0·15	0·75–1·75	0·4–1·0	—	Annealed	9·0	13·0	3·0	65
ZT1	—	—	2·5% nom	—	—	0·7% nom	3·0% Th nom.	Heat treated	5·5*	12·0	5·0	50
TZ6	—	—	5·8% nom.	—	—	0·7% nom.	1 8% Th. nom.	Heat treated	9 5	17·0	5·0	65

* Not specified—for information only

continuous solid solution. It has been proposed for wrought alloys in conjunction with zirconium. The cold forming properties of cadmium containing alloys appear to be slightly better in some respects to those based on zinc. However, such alloys have not so far shown sufficiently interesting properties to make them of commercial interest.

TABLE 2

American Magnesium Alloys fo

Chemical Composition

Specification		Chemical Composition %					
ASTM B80–53T Alloy	Nearest British Aircraft Specification	Al	Zn	Mn (min.)	Rare Earths	Zr	Others
AM80A	L121	7·8–9·2	0·3 max.	0·15	—	—	Imps
	L122	”	”	”	—	—	”
	—	”	”	”	—	—	”
AM100A	L125	9·3–10·7	0·3 max.	0·10	—	—	Imps
AZ63A	—	5·3–6·7	2·5–3·5	0·15	—	—	Imps
	—	”	”	”	—	—	”
	—	”	”	”	—	—	”
	—	”	”	”	—	—	”
AZ91C	L123	8·1–9·3	0·4–1·0	0·13	—	—	Imps
	L124	”	”	”	—	—	”
	L125	”	”	”	—	—	”
AZ92A	L123	8·3–9·7	1·6–2·4	0·10	—	—	Imps
	—	”	”	”	—	—	”
	L124	”	”	”	—	—	”
	L125	”	”	”	—	—	”
EK30A	—	—	0·3 max.	—	2·4–4·0	0·2 min.	Imps
EK41A	DTD.728	—	0·3 max.	—	3·0–5·0	0·4–1·0	Imps
	—	—	”	—	”	”	Imps
EZ33A	DTD.708	—	2·0–4·0	—	2·5–4·0	0·5–1·0	Imps
M1B	DTD.140B	—	—	1·20	—	—	Imps
ZK51A	DTD.721	—	3·6–5·5	—	—	0·5–1·0	Imps
ZK61A	—	—	5·5–6·5	—	—	0·6–1·0	Imps
†HK31A	—	—	—	—	—	0·6–1·0	3·0–4·0 Th
†HZ32A	ZT1‡	—	2·0–2·5	—	—	0·6–1·0	2·5–3·5 Th
†ZH62	TZ6‡	—	5·7% nom	—	—	0·7 nom	2% Th of 1·8 (nom)

*Not specified.

†Proposed designations for materials not included at time of writing.

‡Commercial designation—specification in course of preparation.

Note. Properties refer to specimens tested without removal of cast skin.

Physical and Mechanical Properties

For convenience of reference, composition, minimum mechanical properties and Brinell hardness, have been summarized; Table 1 gives details of materials covered by British Specifications and Table 2 American ones, other properties including compression properties,

Sand Castings—ASTM (Tentative) B80-55T and Minimum Mechanical Properties

Temper	Condition	Minimum Mechanical Properties				
		0·2% Yield Stress		Tensile Strength		Elong. on 2 in. %
		lb./ sq.in. × 10^3	Tons/ sq.in.	lb./ sq.in. × 10^3	Equiv. tons/ sq.in.	
F	As cast	*	—	23	10·2	3
T4	Solution treated	*	—	34	15·1	7
T6	Fully heat treated	12	5·3	34	15·1	4
T6	Fully heat treated	17	7·5	34	15·1	*
F	As cast	*	—	24	10·7	4
T5	Artificially aged	11	4·9	24	10·7	2
T4	Solution treated	*	—	34	15·1	7
T6	Fully heat treated	16	7·1	34	15·1	3
F	As cast	*	—	18	8·0	*
T4	Solution treated	*	—	34	15·1	7
T6	Fully heat treated	16	7·1	34	15·1	3
F	As cast	*	—	20	8·9	*
T5	Artificially aged	11	4·9	20	8·9	*
T4	Solution treated	*	—	34	15·1	6
T6	Fully heat treated	18	8·0	34	15·1	1
T6	Fully heat treated	14	6·2	20	8·9	*
T5	Artificially aged	14	6·2	20	8·9	*
T6	Fully heat treated	16	7·1	22	9·8	1
T5	Artificially aged	16	7·1	22	9·8	1
F	As cast	*	—	12	5·3	3
T5	Artificially aged	20	8·9	34	15·1	5
T6	Fully heat treated	25	11·1	40	17·8	5
T6	Fully heat treated	16	7·1	32	13·4	6
T5	Artificially aged	13	5·9	30	14·3	6
T6	Fully heat treated	21	9·4	38	17·0	6

TABLE 3

Mechanical Properties of Magnesium Casting Alloys at Elevated Temperatures [6, 7, 8]

(*a*) *Alloys for use at normal temperatures*

Alloy		20°C.		150°C.		200°C.	
British Aircraft Specification	Equivalent A.S.T.M. B80–53T	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.
L121	AM80-F	5·1	10·2	4·8	9·6	4·6	8·3
L122	AM80-T4	4·8	16·0	4·3	13·5	4·0	9·3
L123	AZ91C-F	5·5	10·0	5·1	9·5	4·6	8·5
L124	AZ91C-T4	5·3	15·0	4·6	12·0	4·2	9·3
L125	AZ91C-T6	7·5	15·5	5·8	11·0	4·8	8·1
DTD.140B	M1B	1·6	6·8	1·5	5·6	1·5	4·5
DTD.711	ZK51A-T5	—	—	—	—	—	—
DTD.721	ZK51A-T6	—	16·3	—	9·7	—	7·3
DTD.748	—	8·2	14·1	7·2	10·3	6·3	8·5

(*b*) *Alloys for use at high temperatures*

Alloy		20°C. (70°F.)		200°C. (400°F.)		250°C. (482°F.)		300°C. (572°F.)	
British Aircraft Specn.	Equiv. A.S.T.M. B80-53T	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.	0·1 % P.S. tons/sq. in.	U.T.S. tons/sq. in.
—	EK30A-T6	6·1	10·0	4·5	9·0	—	—	—	—
DTD.728	EK41A	6·3	10·0	4·8	10·0	4·2	8·2	—	—
DTD.708	EZ33A	5·5	10·8	4·0	8·4	3·9	7·2	2·7	5·5
ZT1	HZ32	6·0	14·0	—	—	3·2†	5·3†	3·0 (2·7)*	4·8 (4·3)*
—	HK31	7·5	13·4	6·2	10·2	—	—	5·3	8·2

†Properties at 275°C. (530°F.) *Properties at 350°C. (660°F.)

fatigue properties (based on Wöhler fatigue tests) and impact values are given in Table 5. It will be seen that all magnesium alloys are rather notch sensitive under conditions of sudden impact although the effect on fatigue is less marked. Proper design can avoid any difficulties on this account and the use of large quantities of magnesium sand and die castings (to BS.L122) for aircraft landing wheels shows that the high impact resistance of the alloy can be utilized to advantage with confidence.

TABLE 4

Creep Data for DTD708 (EZ33A) and ZT1 (NZ32A) Alloys

Alloy	Test tempera-ture °C.	Time hours	Stress (tons/sq. in.) to produce creep strains of:—		
			0·1%	0·2%	0·5%
DTD.708	200	300	4·10	—	—
(EZ 33A)		500	3·45	—	—
	250	100	1·50	1·83	—
		300	1·30	1·63	1·92
		500	1·15	1·48	1·90
	315	100	0·35	—	—
		300	0·29	0·40	—
		500	0·25	0·38	—
Elektron ZT1	300	100	2·10	2·60	3·25
(HZ 32A)	325	100	1·30	1·75	2·30
	350	100	0·95	1·20	1·40
		300	0·70	0·80	1·10
		500	0·60	0·77	0·98

Apart from room temperature properties the demands of the gas turbine industry have stimulated much interest in the high temperature properties of casting alloys. This has led to the development of alloys already mentioned which have outstanding high temperature properties. The tensile strength of these alloys at various temperatures is recorded in Table 3. These figures should be taken in conjunction with the creep properties shown in Table 4.

Whilst recording mechanical properties it may also be of value to include some physical properties which may also be of importance to the user of castings. Most of these properties vary little over the range of alloys so that the differences between them are small. The following figures (Table 6) give the range of physical properties

TABLE 5

Alloy		Compression properties		Fatigue properties 50 × 10⁶ cycles		Impact values† (ft. lb.)	
British Aircraft Specification	Equivalent A.S.T.M. B80-55T design	0·1 % proof stress tons/sq. in.	Ultimate compression stress tons/sq. in.	Unnotched ± tons/sq. in.	Notched* ± tons/sq. in.	Unnotched	Notched
L121	AM80F	5·1	20·0	5·5	4·0	2·6	1·1
L122	AM80-T4	4·8	24·0	5·7	4·5	15·5	4·0
L123	AZ91F	5·5	20·0	5·5	4·2	1·4	0·6
L124	AZ91-T4	5·3	25·0	6·0	5·0	6·5	2·5
L125	AZ91-T6	7·5	28·0	4·7	4·0	2·3	0·9
DTD.140B	M1BF			3·8‡			
DTD.711	ZK51A-T5	7·0–8·5	22·0–24·5	4·8–5·3	3·8–4·3	8·0–11·0	2·5–3·5
DTD.721	ZK51A-T6	9·0–11·0	23·0–27·0	5·0–5·5	4·8–5·5	5·0–9·0	2·0–3·0
DTD.748	—	7·5–8·5	21·5–23·5	6·0	5·0	3·0–4·0	0·5–1·5
DTD.728	EK41A	6·0–7·0	18·0–22·0	4·2	3·5	—	—
DTD.708	EZ33A	5·0–7·0	18·0–22·0	4·3–4·8	3·3–3·8	5·0	1·0
ZT1	HZ32A	5·0–6·0	20·0–21·0	4·5	4·5	5·0–6·0	1·0–2·0
TZ6	ZH62A	—	—	5·3	5·0	6·0–8·0	1·0–2·0

*Notch stress concentration factor = 2. †Determination made on Hounsfield machine with round of specimens—equivalent Izod figures. ‡Value for 10 × 10⁷ cycles.

obtained with commercial alloys. For more exact figures for individual alloys, reference books or manufacturers' data sheets should be consulted.

TABLE 6

Physical Properties of Magnesium Casting Alloys

Property	Value
Modulus of elasticity (E)	6·5 × 10^6 lb./sq.in. (20°C.)
Modulus of rigidity (G)	2·5 × 10^6 lb./sq. in. (20°C.)
Poisson's ratio	0·3
Density	1·79–1·83
Weight (lb./sq. in.)	0.0646–0·0657 lb./cu. in.
Specific Heat	0·23–0·25 cals/gm.
Thermal conductivity (20°C.)	0·18–0·12 C.G.S. units
Coefficient of thermal expansion	27·0–28·1 × 10^{-6} in/m./°C.
Electrical resistivity	12·8–16·4 ohm/cm^3 × 10^{-6}
Casting shrinkage	1·04–1·33%

REFERENCES

[1] W. HUME-ROTHERY. *The Structure of Metals and Alloys.* Institute of Metals (London), Monograph No. 1.

[2] Institute of Metals, Annotated Equilibrium Diagram No. 5. (1946).

[3] Gmelins Handbuch No. 27 (8th Edition 1952), p. 483.

[4] G. A. MELLOR. The Constitution of Magnesium-Rich Alloys of Magnesium and Zirconium. *J. Inst. Metals* (1950), 77, 163–74.

[5] J. L. HAUGHTON and J. H. SCHOFIELD. *J. Inst. Metals* (1937), **60,** 339–44.

[6] 'Elektron' Magnesium Alloys Handbook, 1953. Magnesium Elektron Ltd.

[7] R. G. WILKINSON. The Status of Magnesium and its Alloys. *Metallurgia* (1953), **48,** 290, 282–8.

[8] F. P. STREITER. Magnesium Casting Alloys containing Zirconium. *Metal Progress* (1953), **63,** (3), 75–82.

CHAPTER 3

Magnesium Alloy Melting Practice

MAGNESIUM ALLOYS are usually poured within a temperature range 700°C.–780°C. (1292°F.–1436°F.). The superheating process is normally performed at a temperature of 900°C. (1652°F.). It is apparent, therefore, that temperatures required by the molten metal are not excessive and, in fact, compare with those required for aluminium alloy founding.

Magnesium alloys can be melted in iron or steel crucibles for there is practically no iron pick-up. Even after several remeltings the iron content does not appreciably increase. The commercial introduction of magnesium alloys of super-purity necessitates modifications to the present technique since small amounts of iron appreciably decrease the corrosion resistance of high purity magnesium. Normally a 'seasoned' crucible (i.e. one which has been used several times for melting normal purity metal) would be used for high purity alloys.

It has been pointed out that magnesium alloys oxidize readily at elevated temperatures, and the first requirement, therefore, of magnesium alloy melting is to prevent excessive oxidation. This is achieved by the use of a flux cover which, when molten, floats on the surface of the metal, effectively sealing it from the atmosphere. Fluxing treatment with specific chemical salt mixtures is therefore an essential part of the melting technique of this metal in distinction to the more or less optional use of fluxes in the melting of other metals.

Development of Melting Fluxes

In general, the use of flux is two-fold; first, to protect from oxidation during the initial melting operations, and second, to effect refining by removal of certain impurities prior to pouring. In order to protect the metal during melting, it is added to the solid metal as it is charged into the pot. Since the melting point of the flux mixture is lower than that of the alloy, by the time the metal is molten, it will be covered by the flux added with the charge. If, of course, there are any surface areas not covered further flux is added.

The metal is so readily oxidizable that some oxidation will take place in spite of the initial use of flux. If this is not removed from the melt, resultant castings will contain oxide inclusions which act as planes of weakness. A further amount of flux is added to the surface after first removing the cover which consists of flux which has accumulated during the melting process. This flux is allowed to melt and then it is vigorously stirred into the metal, with the result that the metal is purified by absorption of the oxide by the flux.

Magnesium melting fluxes nearly always contain anhydrous magnesium chloride, but because of the high melting point of this substance (710°C.), additions of other salts are made to reduce the melting point to a convenient value. With the addition of these further constituents there is also opportunity afforded to adjust the properties of the fluid flux, so that when molten it should not be too fluid, for then there will be difficulty in separating it from the metal.

Early magnesium melting was so carried out with the aid of anhydrous carnallite, a double salt consisting of roughly 60 per cent magnesium chloride and 40 per cent potassium chloride by weight. This flux was very fluid and could only be used with success when there was sufficient oxide to be removed from the melt to thicken it, thereby increasing its viscosity to such an extent that easy separation from the metal was achieved. If, however, the metal under treatment did not contain sufficient oxide, the fused carnallite remained fluid and it was difficult to remove without contamination of the metal. The complete and certain removal of flux compounds was soon found to be of the utmost importance; small amounts of chloride-bearing salts in the body of castings became centres of corrosion in humid atmospheres.

The addition of magnesium oxide to the metal was proposed so that then the flux would thicken sufficiently to make separation certain. In this case, the thickening of the flux was thus controlled to some extent, and did not depend upon the presence of sufficient oxide contained within the original metal, or formed during the initial melting stages. The act of thickening and making more viscous, applied to magnesium melting fluxes, is called 'inspissation': this term has become part of the vocabulary of magnesium metallurgy. Inspissating fluxes, therefore, are those which thicken up during use, regardless of the amount of oxide to be removed from the melt. Many substances have been proposed as inspissators; in addition to the magnesium oxide mentioned above, magnesium flouride is also often added to magnesium melting fluxes. Frequently calcium flouride is used instead of the more expensive magnesium flouride since in the presence of an excess of molten magnesium chloride double decomposition takes place and magnesium flouride and calcium chloride are found.

$$\underset{\text{calcium fluoride}}{CaF_2} \quad + \quad \underset{\text{magnesium chloride}}{MgCl_2} \quad \rightharpoonup \quad \underset{\text{calcium chloride}}{CaCl_2} \quad + \quad \underset{\text{magnesium fluoride}}{MgF_2}$$

An early flux composition[1] based on thickening a carnallite flux with fluorides contained the following:

Flux A	%
Magnesium chloride	68·0
Potassium chloride	28·5
Sodium fluoride	4·5
Calcium fluoride	3·0

The actual composition of the flux will depend to a large extent upon the melting and refining technique used as well as the condition of the metal being melted. For some years a number of foundries have operated with two fluxes—the first a fluid flux, giving good protection during melting and the second an inspissated one added at the refining stage.

These are typified by the following two fluxes patented by Magnesium Elektron Ltd:[2]

Flux B (Melting)	%	*Flux C* (Inspissated)	%
Magnesium chloride	34	Magnesium chloride	40
Calcium chloride	30	Calcium chloride	14
Sodium/Potassium chloride	35	Sodium chloride	6·5
		Potassium chloride	7
Magnesium oxide	1	Magnesium oxide	12·5
		Calcium fluoride	20

In the United States, and to a limited extent elsewhere a different type of flux is used, mainly for diecasting. It is very fluid and remains so for a long period so that when the ladle is dipped into the pot the flux cover is momentarily broken but reforms as soon as the ladle is removed. About 10 per cent by weight of the metal is used. The nominal composition of this mixture[3] (known as Dow 230) is:

Flux D (Dow 230)	%
Potassium chloride	55
Magnesium chloride	34
Calcium chloride	9
Calcium fluoride	2

More recently there has been a trend in some foundries towards the use of a single all-purpose flux which is fluid during melting, refines adequately and becomes more viscous during superheating or on standing.

The compositions of the next two fluxes, one American and the other British, correspond to mixtures of this inspissated type.

Flux E (Dow 310)	%	*Flux F*[4]	%
Potassium chloride	20	Magnesium chloride	45
Magnesium chloride	50	Sodium/Potassium chloride	37
Calcium fluoride	15	Magnesium fluoride	18
Magnesium oxide	15		

Early magnesium castings contained flux inclusions and were undoubtedly responsible for apparently low corrosion resistance of the material. Rapid deterioration of castings, even in indoor locations, due to hydrolysis of the magnesium chloride, forming hydrochloric acid which in turn formed further magnesium chloride was often reported.

$$(1)\quad MgCl_2 + 2H_2O \rightarrow Mg(OH)_2 + 2HCl$$
$$(2)\quad Mg + 2HCl \rightarrow MgCl_2 + H_2$$

For many years magnesium castings have been made which have shown themselves to be completely free from such inclusions. In spite of the chemical activity of magnesium it has been demonstrated that in industrial atmospheres magnesium alloys are better than steel and even in marine atmospheres, given suitable protection, they perform satisfactorily.

Function of Melting Fluxes

For some years it was not known at what stage in melting and casting these inclusions arose, and in fact it was not until 1949 that a paper by Emley[5] demonstrated beyond doubt the origin of these inclusions. In his account he described experiments in which attempts were made to deliberately introduce flux inclusions into the melt prior to pouring. It was found that given a few minutes the inclusions would separate themselves from the metal without the assistance of any external agent such as agitation by stirring. The author's surprising conclusion was 'that contrary to general belief, inclusions of oxide or flux found in castings do not arise from oxide or flux suspended in the body of the metal prior to pouring, whether or not flux refining has been used, but that inclusions can arise at the time of casting.'

It would seem, therefore, that a magnesium melting flux must have a melting point below 620°C. and a density of greater than 1·50 which is the approximate density of magnesium at its melting point. The surface tension of molten magnesium is 502 dynes/cm.[6] at 680°C., so that for wetting of the metal to occur (essential for the protection of the surface from oxidation) the surface tension of the flux will have to be appreciably lower. Whilst the constituents must have a suitably low melting point the mixture must also be reasonably stable up to the maximum superheating temperature (*c.* 950°C.). Emley's work shows that the relative viscosity and surface tension of the flux and molten metal is more important than any other factor. The main compositions listed previously fulfil these requirements.

The conclusions reached by the author, however, give a new significance to the investigations of a French metallurgist Hardouin,[7] who proposed melting under a carnallite type flux, thickening at the refining stage with magnesium fluoride, then removing all flux residues from the melt and covering with a chloride free salt mixture consisting of 85 per cent sodium borate ($NaBO_3$) and 15 per cent boric anhydride (B_2O_3) fused together and crushed to a fine powder prior to use. Thus even if small particles of flux were carried over into the mould there would be no corrosion due to the absence of chlorides.

Studies of the function of magnesium melting fluxes suggest that in the first place a magnesium flux protects the metal from oxidation. Secondly the flux probably removes the larger particles of solid impurities by wetting them, since they normally have a high surface tension, thus causing them either to rise to the surface or sink to the bottom depending upon their relative densities. With the smaller particles suspended in the melt such as oxides, nitrides or sulphides, stirring of the flux into the melt probably causes precipitation of these particles.

It has also been suggested that fluxing has a similar action to that of isinglass or gelatine added to newly fermented beers and wines for the purpose of 'clearing' them. When these agents, known as 'fining', are setting to the bottom of the liquid after mixing, impurities are absorbed into the jelly-like mass and they therefore settle out.

Grain Refinement

After refining is complete the metal is treated to produce grain refinement, and only recently has the mechanism been explained adequately. A paper by Fox and Lardner[8] showed conclusively that grain refinement of magnesium alloys by superheating was confined to those containing aluminium. They also demonstrated that long holding times at temperatures of 850°–900°C. caused grain coarsening and even a short holding period (about 5 min.) at 950°C. was equally harmful. Subsequent work by Baker[9] appears to confirm earlier American suggestions[10, 11] that the nuclei responsible for grain refinement are probably aluminium carbide, iron and manganese compounds.

Investigations into the grain refining of other metals, particularly aluminium, have shown that for such refinement to occur the metal added either of itself or as a compound it produces in the metal, must provide a large number of nuclei so that crystallization proceeds rapidly from a large number of small centres and not slowly from a small number of points. To be effective the grain refiner must have a crystal lattice similar in size and characteristics to that of magnesium.

Now aluminium carbide, referred to above, has a hexagonal crystal lattice as does magnesium, in which the closest distance of approach between the aluminium ions is 3·33Å as compared with 3·20Å between the magnesium atoms in the close packed planes. In the case of iron and manganese the mechanism is probably similar since on superheating they may form a $(FeMn)Al_4$ compound of hexagonal crystal structure as this phase is present at temperature upwards of 710°C. and would be expected to be retained on very rapid cooling, thus providing the necessary nuclei. The evidence to support this contention is still rather indirect and inadequate.

The case of zirconium is interesting since it is a metal having very similar lattice constants to magnesium and solubility which increases with temperature even above the melting point. The grain refinement is probably due to precipitation of small zirconium particles due to their decrease solubility with falling temperature. When aluminium is present a compound $ZrAl_4$ is formed which does not have a similar crystal structure so that in aluminium containing alloys zirconium does not give grain refinement. It is used for grain refining of alloys containing zinc either alone, or in conjunction with rare earth metals or thorium, which do not respond to grain refining by superheating.

It is interesting to note that during the Second World War the Germans used ferric chloride additions to magnesium melts to produce grain refinement.[12] This practice has dangers for the foundry since ferric chloride is hygroscopic and there is an explosion hazard if water is present. Equally important is the fact that iron has an important effect in decreasing the corrosion resistance of magnesium alloys.

However, the use of carbon compounds has proved to be the most satisfactory way of producing grain refinement in magnesium alloys containing aluminium. The use of powdered carbon, chlorine-carbon tetrachloride mixtures, acetylene, etc., have been mentioned in the literature. For convenience of application there are advantages in using hexachlorobenzene[13] or hexachlorethane[14] which are solid chlorinated hydrocarbons which are therefore easier to handle and control than gases.

When appropriate, magnesium alloys are usually superheated by raising the temperature to about 900°C. (1652°F.), holding there for a short period and cooling rapidly to pouring temperature. This practice is, of course, peculiar to magnesium technique; with other metals it is desirable to limit the maximum temperature to but a few degrees above that required for casting. A smaller grain size means greater dispersion of the eutectic constituent which is later taken into solid solution on heat treatment. Heat treatment of a casting that has been made from superheated metal is therefore more complete, and adequate solution may be achieved more quickly than in metal of grosser grain. It is obvious also that the machinability will be at its optimum in superheated as-cast metal, although the machining properties of magnesium in any case are so good that the added improvement due to superheating is comparatively small and is not likely to be noticed.

The effect of superheating is persistent; that is, metal of small grain size shows a pronounced tendency to give castings of small grain, even after one melting without superheating. But because the result is a trifle uncertain, standardization of the melting process to include superheating is desirable. The grain refinement due to superheating is lost when the metal is held for long periods at the usual pouring temperature.

The last statement raises a question of considerable practical importance. Since the normal practice for sand casting requirements is to melt in comparatively small crucibles of about 100 lb. capacity, and from which the moulds are poured, no difficulty exists in the observance of the melting process indicated. Where metal, however, is held in reservoir furnaces for gravity die casting, there is a tendency for reversion to large grain to take place before all the metal is used. This would suggest that when melting for gravity die casting it may be desirable to re-superheat the melt after several hours standing which will be unavoidable when small castings are being made.

The problem is eased to some extent by the fact that the speed of solidification of a gravity die casting is quick compared with solidification of metal in a sand mould, and because of this alone the grain size is comparatively small. For many gravity die castings superheating may not, in fact, be necessary, only a practical test can show whether initial superheating and subsequent superheatings are essential. The requirements may be assessed by fracture testing sand-cast test bars during the period in which the metal is in use, visual inspection of the fracture indicating any material enlargement of grain. Of passing interest, it may be worthy of note that production of billets for mechanical working, such as forging or rolling, should be from grain-refined metal.

Gas Absorption

For many years it was thought that magnesium alloys did not suffer from the effects of gas pick-up; it has now been conclusively shown[15] that, firstly, a small amount of hydrogen may be absorbed during melting, and secondly, that this small amount is related to the incidence of micro-porosity. It should, however, be understood that magnesium alloys never suffer from the pinholing associated with gas pick-up in molten aluminium alloys. The complete absence of pinholes in magnesium alloys was indeed the reason for believing that magnesium alloys have no gas solubility. But once the fact was admitted, and its relation to the peculiar magnesium porosity demonstrated, it was but one step to attempt gas removal by the well-known methods employed in molten aluminium alloy technology.

Elemental chlorine was found to be effective in gas removal; chlorine-evolving organic compounds such as hexachlorobenzene and hexachlorethane were further tried and found to be effective, but with the added advantage of also producing grain refinement. This development resulted in many beneficial modifications to magnesium alloy melting technique.[16] Due to the formation of a volatile chloride, alloys containing thorium or cerium should not be treated in this way since complete loss of these metals is possible. In those alloys containing zirconium this is added as a master salt after melting. This is stirred in and then the melt refined by fluxing. After being allowed to stand, it is ready for pouring without superheating.

Gaseous chlorine reacts with molten magnesium to give magnesium chloride, and this reaction of course occurs regardless of whether chlorine as such is bubbled through the melt or whether chlorine is produced by the decomposition of a compound. This magnesium chloride formation is valuable, for during agitation of the melt, it is thrown to the surface where it acts as a flux cover. With the use of suitable organic compounds, therefore, two processes are combined under attractive conditions; degassing is achieved and grain refinement is effected in the temperature range of 700°–750°C. (1292°–1382°F.), and flux consumption is reduced. (See *Figs.* 6 and 8.) With grain refining as normally practised by superheating, the melt is taken to 900°C. (1652°F.) therefore necessitating a considerable increase in fuel costs. The use of an indirect material of considerable expense is thereby greatly reduced. After carrying out grain refinement in this manner an inspissated flux is added and refining carried out in the normal way.

In connexion with the general subject of melting magnesium alloys, there is an aspect of technical importance associated with the small but inevitable melting loss. It appears that the magnesium oxidizes preferentially to the aluminium, and the aluminium content per cent is increased therefore. This fact will be discussed later, but it is worth remarking upon at this point, so that alloys with an aluminium content near the top limit of a specification will not be used.

General Melting Practice

We can now proceed to a detailed description of practice for the preparation of molten magnesium alloy to be used in a sand foundry.

A clean iron or steel pot is warmed in the furnace, which is preferably sunk into the floor of the foundry such that the top of the pot is about a foot above floor level in order that fluxing manipulation may be carried out with comparative ease by foundry operatives. The pots may be made of cast iron, pressed steel, or sheet steel of boiler plate quality fabricated by welding. The iron or steel in each case must be free from nickel because nickel is dissolved by molten magnesium with a deleterious effect on corrosion resistance. Cast iron pots tend to suffer from casting defects such as blowholes in the bottom, while fabricated steel pots are lighter. The choice of pot must remain a personal responsibility, after weighing consideration of price and pot life.

After each day's work the pot should be filled with water to remove incrustations of flux and oxide; it is noticeable during this cleansing operation that there is a pronounced smell of ammonia, presumably due to the decomposition of magnesium nitride. The pot is scraped clean and heated to redness before use. Lack of uniformity in the intensity of the heat-colour indicates discontinuities in the pot, which should be tested by hammering with a blunt-nosed hammer. If the pot can be deformed at the inspected point it should be rejected.

The warmed ingot or clean scrap is placed in the pot which is now in the furnace, a sprinkling of flux being added. The flame is adjusted to give quick melting; as the bottom part of the charge melts, flux should be added from time to time to form a flux cover, thus preventing oxidation and burning. At a temperature of about 750°C. (1382°F.), the heat should be stopped in readiness for the refining operation. By this time no more than 1 per cent of flux by weight of the metal melted should have been added. At this stage the melt may be treated with about 0·05 per cent of a carboneous agent by plunging it into the melt, or in the case of zirconium alloys with the master salt or hardener. (See p. 45.)

The flux cover is now removed with heated mild steel spoons, oxidation of the bare metal surface being prevented temporarily by a sprinkle of powdered sulphur. When the surface of the metal is clean, about 2 per cent of flux should be added and allowed to fuse. The fluid flux is then vigorously stirred into the metal with a heated iron rod for about two minutes (see *Fig.* 6). Refining has been adequately performed when the surface of the magnesium revealed between patches of surface flux has a clean metallic appearance similar to that of mercury. The metal is allowed to come to rest and then the flux on the surface is removed. During refining some flux will have sunk to the bottom and some will have adhered to the pot wall. The molten metal is sometimes cleaned from flux by removing the residue from the side and bottom of the pot with a suitable spoon-shaped tool. Improvements in the knowledge of the mechanism of fluxing suggests that this operation is not usually necessary. A further quantity of flux should now be added to the surface of the metal and allowed to fuse. About 2 per cent of the weight of the metal charge in flux should again be added, this quantity being adequate to provide protection during pouring. Where the old technique of grain refining by superheating is preferred the metal is now heated as quickly as possible to a temperature of 850°–900°C. (1560°–1650°F.), held at this temperature for about 15 minutes, and then cooled as quickly as possible to pouring temperature. It will, therefore, be advisable to lift the pot from the furnace so that cooling proceeds more quickly. It may be quite a good plan to equip the foundry with a hollow shell into which the pot of superheated metal may be placed, so that compressed air may be directed suitably around the pot to achieve

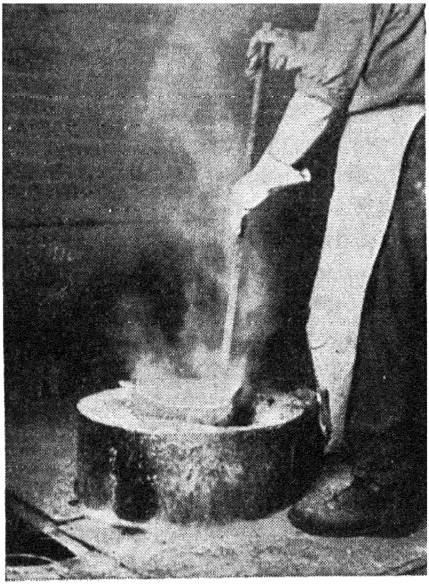


Fig. 6. Flux refining a pot of molten magnesium.

quickest possible cooling. If this equipment were made portable it could be used at any desired furnace position.

At some 10°C. (20°F.) above pouring temperature the flux cover is removed; it will now be found that the flux cover has hardened to some degree and may be therefore lifted from the metal without fear of contaminating it by dropping from the spoon. Before the flux cover is removed the pot should have been brushed with a steel brush to remove dried flux particles. If the brushing is directed to the centre of the pot, such foreign matter will be collected on the flux cover and so removed with it. Foundry tests must be made to determine the temperature at which the flux cover should be removed in order that the metal may arrive at the mould at the correct pouring temperature if it is found that the temperature 10°C. above pouring temperature suggested is not sufficient. The surface of the metal should be kept protected either by dusting with a sulphur-boric acid mixture, or a cover containing a reservoir of sulphur to provide sulphur dioxide.

The foregoing description of the melting process is based upon the assumption that a flux similar to Flux F is in use. Other fluxes, of different characteristics, will require slightly different procedures. For example, alternative common practice is to use a flux in which hardening of the surface cover is less marked or indeed absent. In this case, no attempt is made to remove the flux cover prior to pouring. It continues to act as a protection against oxidation. As the pot is tilted carefully and smoothly to pour, the non-solid flux cover actually moves with a slight backward motion away from the lip of the pot, and, therefore, flux contamination need not be feared. The pot, however, should not be completely emptied of metal.

Whilst the above description represents typical sand foundry practice a development first reported in the United States[3] is the use of large reverberatory furnaces for melting 6 to 10 tons of magnesium either as ingot for casting into rolling slabs etc., or for the refining of magnesium scrap or alloying on a large scale. Obviously with a sufficiently large output it could be used as the central melting unit for large sand or die-casting foundries. Melting is carried out under a fluid-type flux such as Dow 230 (Flux D) and in the foundry operations such as refining and inoculation with a grain refining agent are more readily carried out in smaller crucibles. However, since the reverberatory furnace has a refractory lining it is particularly suitable for handling high purity alloys.

We have now a pot of refined (superheated) magnesium at some furnace position and which has to be taken to the mould for pouring. Some protection therefore has to be given the metal after the removal of the protective flux; flowers of sulphur liberally sprinkled on the surface achieve this, and, of course, if signs of oxidation appear, further sulphur should be added. The protection given by sulphur is often permanent enough to be satisfactory, but, of course, there is present the nuisance factor of the pungent sulphur dioxide odour. In order to combat this, and following the search for more permanent protection of molten metal in the uncovered condition, some American practice uses a dusting compound consisting of fluorides and boric acid; this compound forms a thin protective film and disagreeable fumes are not evolved. A further advantage is that the film formed is chemically inert to magnesium and does not cause corrosion if any of the film becomes entrained in the metal stream during pouring, although the tenacious skin formed tends to give trouble in castings, forming local points of weakness.

Even where a protective flux cover is maintained dusting with a sulphur-boric acid mixture is necessary to avoid excessive oxidation of the exposed metal where the flux has broken and does not protect the metal. At the pouring station the metal is poured without breaking the flow into the prepared mould, the metal stream being dusted with either sulphur or the dusting powder described above. (See *Fig.* 7.)

The appearance of the pot after pouring is instructive, and such inspection provides a check that the flux is working properly and the fluxing process is being performed efficiently. It will be found, if the sludge removing technique is used, that the walls of the pot are quite clean and free from adherent flux and that the bottom of the pot is clean also, although on occasion it will be found that a small flux deposit is present. In spite of careful fluxing technique, there is some evidence that the flux particles, remaining suspended in the metal after scavenging the pot, settle out during the superheating period. It is good practice not to empty the pot completely so that this precipitated flux sludge will not be carried over into the mould. At the end of the day's work, the pot should be carefully inspected for weakness as described above. Metal and flux incrustations are removed by soaking in water. After cleaning and inspection the pot is dried and is ready to be used again.

Where the alternative technique is used it is preferable to pour the last metal in the pot into a pre-heated ingot mould. The flux residue will remain in the bottom and can be removed together with any residue on the pot walls by scraping with a suitably shaped tool.

There is always some melting loss and it appears that this melting loss consists of magnesium in the normal alloys; there is, moreover, analytical evidence that the aluminium content tends to increase and this fact must be remembered when using alloys containing aluminium near the specification top limit, and also in the remelting and use of foundry scrap. In the creep resistant alloys, cerium and thorium tend to be lost due to preferential oxidation.

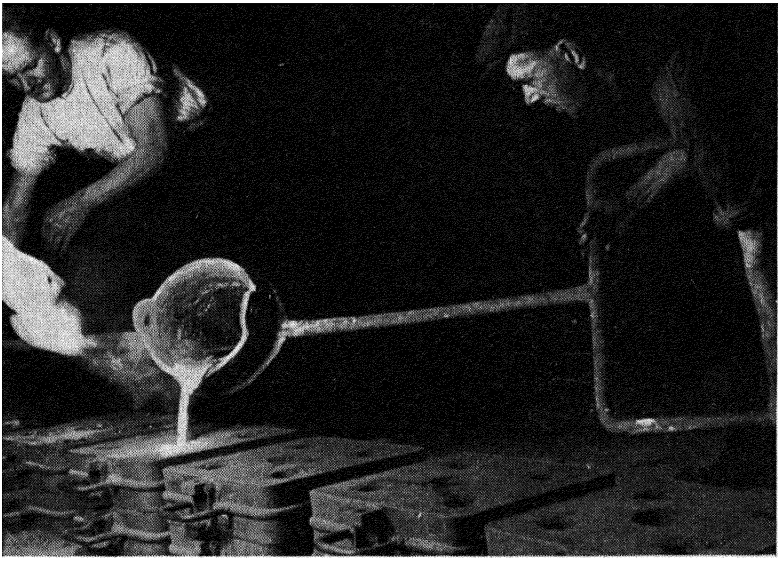


Fig. 7. Pouring molten magnesium into a sand mould. In the left of the picture can be seen the bag containing a dusting powder to minimize oxidation.

Alloying

A word may be added here on the methods of alloying magnesium alloys. The usual foundry alloys contain between 6 per cent and 11 per cent aluminium, up to 3 per cent zinc, and about 0·2 per cent manganese. Little difficulty will be experienced in the compounding of these alloys. The constituent metals are weighed out and the magnesium melted. The melting point of pure magnesium is 650°C.

(1202°F.), while the melting points of aluminium and zinc are 660°C. (1220°F.) and 419°C. (786·2°F.) respectively. Zinc is added as soon as the magnesium is molten. The temperature of the metal should now be adjusted to about 700°C. (1292°F.) and the aluminium added with stirring.

Manganese may be added as an aluminium-manganese hardener, a compensating reduction in the amount of virgin aluminium added made in this case; or by the addition of anhydrous manganese chloride which is reduced to metallic manganese within the melt by chemical reaction with the magnesium.

An excess of manganese chloride is added above that theoretically required: as an example, if an addition of 1 lb. manganese is to be added, then about 4 lb. of the water-free manganese salt will be required.

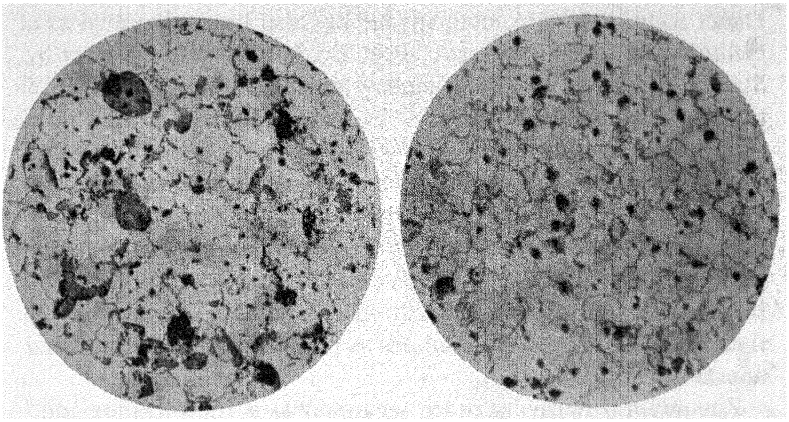
During the alloying process the flux cover is maintained on the melt to prevent oxidation. American practice favours the incorporation of the manganese by using a flux which allows the formation of magnesium chloride from the decomposition of manganese chloride and will have a composition similar or compatible with the standard flux when alloying is complete. A flux consisting of:

	%
Manganese chloride	76
Calcium fluoride	13
Magnesium oxide	11

It is recommended for use in conjunction with Dow 310 (Flux E) composition.

Magnesium alloys do not suffer from segregation to any marked degree, but samples for analysis must be taken with care, especially when the sample is prepared by pouring into a chill mould, as the surface layer of the ingot may be found to be excessively rich in manganese.

The development of magnesium alloys containing zirconium has been the outstanding achievement of the post-war period. Zirconium is a grain refiner that is effective in the presence of zinc, cerium and thorium but not aluminium. For some time the difficulty that remained to be solved was a satisfactory method of adding the element to give a high level of dissolved zirconium without a big loss of zirconium and the production of flux inclusions which were almost impossible to remove from the metal.



(*a*) (*b*)

(*a*) Photomicrograph of L 123 (Mg–10% Al) after superheating. (*b*) Photomicrograph of L 123 (Mg–10% Al) after grain refining with hexachlorethane.

Fig. 8

In Great Britain[17] a technique has been developed which is based on the transfer of zirconium to the molten metal by means of a master salt which is prepared from zirconium fluoride, which is dissolved in a mixture of alkali and alkali earth fluorides. The master salt is added as a flux during melting, but the amount added must be controlled so as to ensure sufficient zirconium being present. It is stirred into the melt after melting is finished to produce alloying. An important factor in ensuring maximum transfer is the metal temperature which should be rather higher than that used for flux refining of the aluminium containing alloys, and 780°–800°C. is usually employed. A small amount of master salt may be dusted on the surface during stirring to prevent undue oxidation, or else a dusting powder employed.

After stirring in the master salt it is desirable to cast a small test piece which is quickly cooled after solidification and fractured to check grain size. It is unusual to have an unsatisfactory result if sufficient master salt has been used, but in such an event a further addition should be made.

There are some differences of opinion as to the merits of this process as against the technique of adding a magnesium-30 per cent zirconium hardener, prepared by reducing zirconium chloride with molten magnesium, as developed by the Dow Chemical Company.

Direct addition of zirconium sponge has also been advocated as a method of producing a master alloy. *Fig.* 9, taken from a paper by Streiter[18] of Dow Chemical Company, shows the relative efficiency of transfer of zirconium to the melt by various processes. These data appear to suggest a lower efficiency for the fluoride technique. However, British workers are of the opinion that the efficiencies obtained both from the chloride agent and the fluoride mixture are low due to the temperature being too low and the stirring inefficient. The fluoride mixture used is considered inferior to the master salt employed in this country. Further independent work to establish more precisely the relative merits of these methods as production techniques would appear desirable.

Zirconium is normally added separately as a grain refining addition after melting and as near to pouring as possible. The presence of any appreciable magnesium oxide in the melt or a high hydrogen content can cause the zirconium to be precipitated, and these can arise from the use of damp, dirty metal or tools as well as damp fluxes, so that the precautions already mentioned are particularly important in this case.

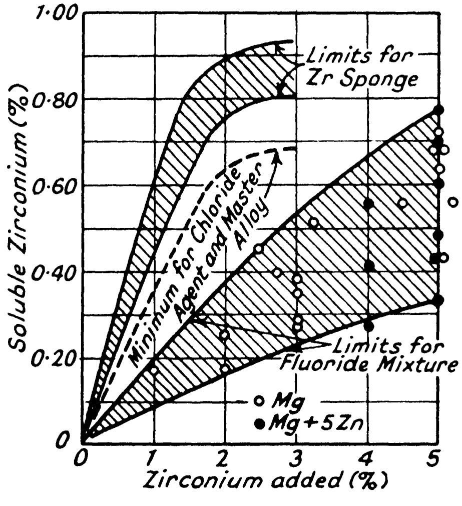


Fig. 9. Graph showing relative efficiency of alloying zirconium with magnesium by various methods.
i.e. (i) Using fluoride salts mixture.
(ii) Adding via chloride agent and master alloy.
and (iii) Direct addition of zirconium sponge [According to Streiter.[18]]

Cerium can be added direct to the melt without the use of an intermediate master alloy although this is preferable. The addition of cerium makes the melt more liable to oxidation and there can be further loss due to a slight reaction with the melting flux. Chlorination of the melt must not be used since this will remove cerium in the melt as chloride. Any losses of cerium can be remedied with the addition of an appropriate amount of hardener.

Thorium is normally introduced into magnesium as a master alloy, prepared by the reduction of thorium salts, and it usually contains about 20 per cent thorium; it has also been added direct as sintered metal to produce a 20 per cent master alloy. Thorium also tends to increase the reactivity of the melt and generally speaking the addition of the hardener should be carried out at as low a temperature as possible, preferably around 700°C. Once again chlorination must not be used as it will remove the thorium by conversion to the chloride.

REFERENCES

[1] J. D. HAUGHTON and W. E. PRYTHERCH. *Magnesium and its Alloys.* H.M.S.O. (1937).

[2] Brit. Patents 539,023; 561,748; 539,024; 562,597; 562,636.

[3] C. E. NELSON. *Melting and Refining Practices for Magnesium.* American Institute of Mining and Metallurgical Engineers, New York (1946). Symposium of Non-Ferrous Refining Practices.

[4] British Patent 548,381.

[5] E. F. EMLEY. *J. Inst. Metals* (1948–9), **75**, 431–80.

[6] A. BECK. *Technology of Magnesium and its Alloys,* p. 118.

[7] M. HARDOUIN. *Etude des Flux D'Epuration et de Protection du Magnesium et des Ses Alliages.* (1933), Publications Scientifiques et Technique du Ministere du Air (France).

[8] F. A. FOX and E. LARDNER. *J. Inst. Metals* (1945), **71**, 1–22.

[9] W. A. BAKER, M. D. EBORALL and A. CIBULA. *J. Inst. Metals* (1952–3), **81**, 43–48.

[10] C. H. MALONEY, A. L. FARR and P. E. LEGRAND. *Trans. Amer. Inst. Min. Met. Eng.* (1945), **161**, 328–50.

[11] J. A. DAVIS, L. W. EASTWOOD and J. DE HAVEN. *Trans. Amer. Found. Assoc.* (1945), **53**, 352.

[12] *Production and Fabrication of Magnesium Alloys.—I. G. Farbenindustrie Bitterfeld and Aken,* London: 1946. (H.M.S.O.) C.I.O.S. Report, Item No. 21, File No. XXIX-3.

[13] U.S. Patent 2540,366 (1951).

[14] Brit. Patent 606,072.

[15] W. A. BAKER. *J. Inst. Metals* (1945), **71**, 165–204, also E. A. G. LIDDIARD and W. A. BAKER, *Proc. Inst. Brit. Found.* (1944–5), **38**, A63–A77.

[16] W. P. SAUNDERS and F. P. STREITER. *Trans. Amer. Found. Soc.* (1952), **60**, 581.

[17] H. J. MILLWARD. *Metal Ind.* 1953, **83** (5), 83–85.

[18] F. P. STREITER. *Metal Progress* (1953), **63**, 375–82.

CHAPTER 4

Moulding and Core Sands

SO-CALLED SYNTHETIC SANDS, of some attraction for the moulding of any metal, are associated particularly with magnesium alloy technique. The chemical and physical properties of these alloys in the molten condition necessitate safeguards given mainly by synthetic sands of controlled composition.

Characteristics Required

The physical properties of sands suitable for magnesium alloy moulding are governed largely by the incidental chemistry of the metal at high temperatures, although the fact of low specific gravity also must not be lost sight of. The specific gravity at normal temperatures is about 1·8; at 700°C. (1292°F.) the specific gravity is no more than 1·5, so that the fluid metal exerts little hydrostatic pressure. While moulds do not require to be weighted as in cast-iron or the heavier non-ferrous practice, the fact must be recorded that the sand for magnesium moulding should be well vented in a sense quite different from venting normally practised. For momentary back pressures caused by air pockets in recesses of the mould cannot be tolerated: small pressures of no significance in heavier metals may be the cause of much trouble in magnesium work. Sand of the greatest permeability must be used. Synthetic sand provides a means whereby this required 'openness' may be achieved. Natural sands as mined consist essentially of a mixture of silica grains of varying size, and colloidal clays providing plasticity in the moist mass, together with some organic matter. It will be known and appreciated that the distribution of grains in such sands, varying from very small particles, fine enough to be called silt, to large coarse ones, results in low gas permeability because the fine grains pack into the spaces between the large ones.

Again, the clay content and composition of natural sands is variable within wide limits, and consequently the moisture, combined or at least loosely held, varies also. Further, organic matter such as decaying vegetation may be present in appreciable quantities, giving rise to gas evolution when such particles are situated at the mould surfaces as molten metal comes into contact with them.

Natural sand is therefore variable just because it is natural, and it will now be seen that the variations, perhaps of little import where heavy metals are concerned, are of major importance in respect of the low density of chemically active magnesium alloys. There are few natural sands in the world that may be used for magnesium moulding. There are deposits in U.S.A. and Germany, but in the United Kingdom the Bromsgrove deposit is the only natural deposit which has been used in magnesium foundries.

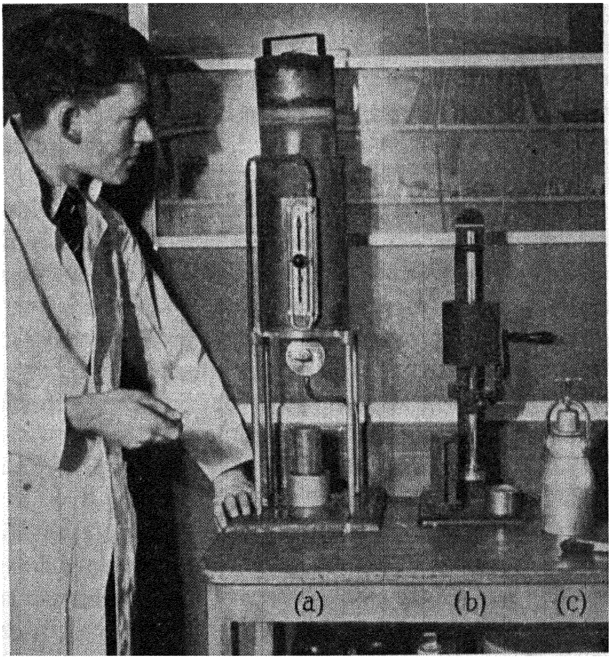


Fig. 10. Testing moulding sand from the magnesium foundry for permeability (i.e. rate of flow of gas through the sand). High permeability is an essential quality of magnesium moulding and too low a permeability results in blowholes and other defects on castings. (*a*) Permeability apparatus (*b*) rammer (*c*) moisture testing apparatus.

The synthetic sand usually used consists of a mixture of washed silica sand, a clay, and water. Additional substances are included in the composition as will be shown later. A sand of mouldable properties can be elaborated from these substances, and because in this sense the product is synthetic, as distinct from a natural product, the composition may be adjusted to give the required combination of properties; what is more, starting with materials of known characteristics, sand of known properties may be maintained. It has previously been hinted that standardization and control are the foundations on which successful magnesium foundry technique are based.

Silica sand of fairly uniform grain size is used, to which is added a known amount of a substance akin to china clay, such as bentonite, and also a known quantity of water. China clays have the property of absorbing large quantities of water to form substances having plastic properties. The clay so formed is lightly milled with the sand, and as each grain becomes coated with a thin film of clay, its influence spreads throughout the sand mass, and a free-running sand is transformed to a material having moulding properties; and again a further measure of standardization is achieved, for moisture in the magnesium moulding sand will always be at a constant level.

This control of moisture is important, for magnesium reacts explosively with water. As previously indicated, magnesium reacts with boiling water to form magnesium oxide with the liberation of hydrogen; how much more vigorous, then, is the reaction at 700°C. (1290°F.), the temperature at which magnesium alloys are used. This fact constitutes one reason for limiting the moisture content of moulding sands for magnesium alloys, but reaction with even this small amount present has to be prevented.

Function of Moulding Sand Inhibitors

Consideration of the fundamental means of preventing oxidation will be instructive here. Where it is desired to prevent oxidation at some elevated temperature, as in bright annealing processes, the operation is conducted in atmospheres from which oxygen or moisture, or both, are removed, or to which large quantities of diluting inert gases are added. In other cases, principally where corrosion generally is to be prevented, metals are protected by protective films, as for example by chemical or electro-deposited films, by paints or enamels, or simply by grease. In short, oxidation is prevented by modification of the surface layer of the metal to be protected. Applications of both systems occur in the various magnesium techniques, and the desired conditions may be secured by addition of chemical agents to the moulding sand. It was these substances that were mentioned above.

The earliest attempts at producing magnesium alloy castings were made with full realization that reaction of the molten alloy with moisture had to be prevented, and the method then adopted consisted in complete drying of the mould by baking at a high enough temperature to evaporate all water. The chemical success of the method was marred by the practical disadvantage that dried sand moulds are extremely friable; resultant castings suffered from numerous sand marks and lack of definition.

It was indeed fortunate that specific sand additions were found that did not materially affect moulding properties, and which enabled the moulds to be filled with molten metal whilst in the 'green' that is undried state. These addition agents are in general known as inhibitors, as their function is to inhibit or restrain the chemical reaction of oxidation between molten magnesium alloy and the moisture in the sand, and also between the air contained within the mould cavity until it is displaced by the cast metal. The term inhibitor is therefore one of two or three terms particularly associated with magnesium foundry technique.

Many substances have been proposed as inhibitors for the purpose under discussion. Sulphur was the first material to be used,[1] followed by a mixture of sulphur and boric acid.[2] The action of sulphur by itself is that of, first, vaporization under the influence of heat supplied by the flowing metal at some temperature around 700°C. (1290°F.) and, secondly, of the formation of the gas, sulphur dioxide so that the resulting gaseous mixture displaces the air within the mould cavity with the result that entering metal is subjected to an atmosphere containing but little free oxygen. Violent oxidation is thereby prevented, as long as sand moisture is kept within some limit and the metal temperature is not excessive. For it may be noted here that sulphur dioxide itself can be decomposed by magnesium that is already burning; but in this case, of course, the temperature is considerably higher than that normally encountered in magnesium founding.

Inhibition by boric acid or borates depends upon the formation of a film on the surface of the molten metal, so that oxygen is prevented from coming into contact with the actual metal. The use of the sulphur-boric acid mixture results therefore in two methods of oxidation protection, and gives a practical safeguard against accidental failure of one system from whatever cause.

Fluorides have also been proposed[3, 4] and used as sand inhibitors. The use of fluorides depends for its success on protective film formation on the molten metal. In order to make sure that the fluoride comes in intimate contact with the metal, ammonium bifluoride or ammonium acid fluoride as it is also called, is often used; this compound—in common with other ammonium compounds—sublimes or vaporizes without passing through an intermediate liquid state at a comparatively low temperature. Actually, ammonium bifluoride dissociates on subliming giving hydrofluoric acid with the formation of a tenuous fluoride skin on the flowing metal. Oxygen is again prevented from making contact with the molten metal. American practice often favours the use of ammonium silicofluoride instead of the bifluoride. There is no doubt from inferences that may be drawn from practical experience that a chemically resistant skin does exist on the surfaces of castings produced in ammonium bifluoride inhibited sand.

From the discussion above, it appears that the sulphur-boric mixture and the bifluoride act in a similar manner—by both film formation and by protective atmospheres. Restraint of oxidation is so important in magnesium melting and in heat treatment processes that a little further discussion of the subject may profitably be given.

Theory of Oxidation Inhibitors

A paper that has become a classic work on the oxidation of solid metals at elevated temperatures was published in 1923 by two American scientists, Pilling and Bedworth,[5] who showed that oxide films of the common engineering metals were either continuous or discontinuous. The former were protective in so far that oxidation was not progressive, while the reverse applied in the case of discontinuous films. It was found that this fact could be represented quantitatively, for if the ratio of molecular density of oxide formed to the molecular density of parent metal was greater than unity, the film was continuous and protective; if the ratio resulted in a value less than unity, the film formed was discontinuous and supplied no protection. It probably does not take many moments' reflection to appreciate the latter statement, as obviously oxygen of the air has no difficulty in gaining contact with the metal lying beneath the oxide film.

The factor arising out of consideration of molecular densities, indicating the type of oxide film, may be variously termed the *Pilling and Bedworth* factor or 'protection coefficient'. In the case of magnesium and magnesium oxide the protection coefficient is less than unity and therefore the oxide film is non-protective: in a word, oxidation is progressive. The case of aluminium is an interesting and contrasting one in which the protection coefficient is greater than unity, and oxidation is therefore limited to the production of a tight oxide envelope, after which oxidation ceases.

It is to be noted that Pilling and Bedworth's work applied to pure metals at elevated temperatures, but below their melting points. There can be little doubt that the conception of these two workers influenced work and thought on the mechanism of oxidation and corrosion protection generally. A French research worker Delavault[6] sought to apply the hypothesis to magnesium in the molten state. It was clear from common experience, of course, that the oxide of magnesium could not provide even temporary protection, and apparently Delavault argued that surface compounds of magnesium with elements other than oxygen might give films having a Pilling and Bedworth factor greater than unity, and thereby giving protection from violent oxidation. Delavault determined or calculated the protection coefficients given by the compounds of magnesium with nitrogen, carbon, sulphur, boron and fluorine. The order of the resulting values was found to be in the following ascending sequence: nitrogen, sulphur, and fluorine, the last named producing a factor well above unity. It is well known that moulding sands containing ammonium bifluoride give castings having a tough, corrosion-resistant skin which is also present on the molten metal as it fills the mould.

The case of sulphur is interesting. Experience again shows that the use of powdered sulphur on the surface of molten magnesium gives what might be described as transient protection, and Delavault shows why this occurs. Sulphur acts in a two-fold manner. First, it forms a sulphide with the molten magnesium: this has a Pilling and Bedworth factor of 1·26; second, sulphur at the temperature of molten magnesium burns with the formation of sulphur dioxide, which again reacts with magnesium to give magnesium sulphate and sulphur, for which combination Delavault gives a factor of 0·92. Subsequent German work[7] in the main confirms this but indicates that a mixed magnesium sulphide and oxide is usually formed in the presence of sulphur and this film may further react with the sulphur dioxide to give magnesium sulphate and sulphur. In passing, it may be noted that the factor for magnesium oxide is 0·71, which is approached as the permeable film allows oxygen to pass, forming in turn more porous oxide film. Sulphur then only retards oxidation, but, as will be shown, there may be advantages accruing from the temporary nature of the inhibition.

Reverting to magnesium fluoride, surface films produced when fluorides are used as oxidation inhibitors, the Pilling and Bedworth factor is given as 1·32. When, however, borofluoride compounds are used, fused nitrides or oxides of boron may be formed, which floating on the surface of the molten metal, give further protection. The combination of magnesium fluoride and boron nitride has a factor of 1·95, while a film composed of magnesium fluoride and boron trioxide has the extremely high factor of 3·1.

It would appear from the above discussion that simple fluorides are the best choice for sand additions. Even then, the film is in fact so tenuous that thin sections of castings are notably prone to cold shutting due to slowing down of the rate of metal flow and imperfect mating of adjacent streams of molten metal. The addition of boric acid would probably only serve to intensify the tendency to casting defects of the type noted, and should not be made therefore. Although some foundries have used fluorides as the sole inhibitor for many years, the general trend is either to use sulphur and boric acid alone or else to use limited fluoride additions in conjunction with the other inhibitors.

Overcoming Drying Out

Synthetic sands containing the inhibiting additions indicated above have been successfully used for many years. Quite apart from their effectiveness in restraint of oxidation, however, these sands suffer slightly from a disadvantage from the moulder's point of view. Moulders accustomed to working in natural sands as commonly used in aluminium or iron foundries complain that silica sand mixes are dry to work. It must be accepted that there is point in this practical criticism and some probationary period, in which he may attain the correct 'feel' for the material, must be allowed the moulder new to the magnesium field.

In further consideration of this aspect of magnesium moulding sand, it is generally accepted that the sand also dries quickly. That is, because of the low moisture content, and the nature of the sand, an open mould loses water rapidly by evaporation at the mould surface, with the pronounced tendency to surface damage by crumbling. Moulds for magnesium alloy casting should not remain open for long periods on the floor, but should be closed and poured as soon as possible. It would appear that moisture is more loosely held in the synthetic mixtures than naturally bonded sands.

Silica sand mixtures detailed in the American Press[8] frequently show the addition of small amounts (0·5–2·0 per cent) of hygroscopic substances, of which ethylene glycol is an example. Such additions are made to combat excessive drying by reason of their capacity to absorb water.

Arising from the foregoing discussion, it will be appreciated that the use of artificially bonded moisture-controlled silica sand compositions, though necessary to the art of magnesium alloy sand casting, nevertheless brings attendant disadvantages. It is believed that the problem may be simply solved, bringing sand technique for magnesium alloys in one step near to the position enjoyed by aluminium and other non-ferrous moulding.

It has been found that when solid boric acid and solid ammonium bifluoride—both substances commonly used as inhibitors—are mixed together, an unexpected reaction takes place, for a wet mass is formed. The reaction may perhaps be symbolized as follows:

$$\underset{\substack{\text{boric}\\ \text{acid}}}{H_3BO_3} + \underset{\substack{\text{ammonium}\\ \text{bifluoride}}}{2\,NH_4HF_2} \rightarrow \underset{\substack{\text{ammonium}\\ \text{borofluoride}}}{NH_4BF_4} + \underset{\substack{\text{am-}\\ \text{monia}}}{NH_3} + \underset{\text{water}}{3H_2O}.$$

The ammonium borofluoride produced is known to act as an inhibitor as shown above; when therefore the required proportions of boric acid and ammonium bifluoride are separately added to the dry sand containing the bonding agent and the whole mixed, the above reaction proceeds within the sand mix, thus effectively adding water and ammonium borofluoride, the ammonia gas escaping to atmosphere.

A sand so prepared[9] has markedly different properties in respect of 'feel' and drying from those to which free water is added separately.

For instance, this sand loses moisture at a much slower rate, and further, it remains mouldable at a free moisture content so low that normal sands would be unworkable. It may be conjectured that the water formed within the mass as the result of a chemical reaction combines more closely with the bonding material than does added water which, in comparison, is but poorly incorporated by such mechanical means as light milling and mixing in a foundry mill.

It has been accepted that it is not easy to repair accidental damage to moulds composed of synthetic sand, and this was largely because of the excessive drying speed of such sand. If, however, sand of the type suggested, that is with moisture added as the result of a chemical reaction *in situ*, is used, minor modifications may be made successfully. One of the incidental problems of magnesium sand casting mentioned above, that of having to pour moulds quickly to safeguard crumbling due to drying, would also be solved by the use of the sand described. Consequent upon the slower drying rate, it may be that better organization of melting and casting can be achieved.

A typical sand mixture utilizing this principle would consist of the following:

	%
Dry silica sand	87·5
Bentonite	3·0
Boric acid	2·5
Sulphur	2·5
Ammonium bifluoride	2·5
Water	2·0

The individual constituents should be added in the order given above. Particular care should be taken to ensure that adequate time is allowed for each agent to be well dispersed in the sand before the next is added. Some ammonia is evolved by the reaction but given reasonable ventilation this is not troublesome. Milling should not be prolonged once the final water addition has been made.

This type of sand has only had limited practical usage but experiences with it have been encouraging. In a comparative test made between a standard sulphur-boric acid inhibited sand and a borofluoride sand as above with both containing 5 per cent moisture it was found after thirty-six hours that the standard sand contained only 1·2 per cent moisture, was friable and unsuitable for moulding. On the other hand the second sand contained 2·2 per cent moisture and was still mouldable although a little drier than would normally be preferred.

The valuable effect of adding water by means of the chemical reaction suggested persists, for following the normal practice of sand aeration and tempering with water after mould knock-out, the original properties reappear: the sand 'feels' right to the moulder, and again does not dry out as quickly as sands to which all the moisture is provided by a free water addition.

Moulding Sand Mixtures

Silica sand consists of practically pure silica. The type used for magnesium moulding should be washed and grain grraded; washed to remove foreign organic matter which would form carbonaceous gases at the temperature of molten magnesium, and graded in order to achieve a high permeability value. Sand received into the foundry should be dry, or it should be dried before use. It has been found that when 80 per cent of the sand is retained by adjacent larger sieves, with the smallest proportion of fines, the permeability will be adequate. For guidance, it may be noted that sieves 44 and 60 may be used as the adjacent test sieves. Fundamentally, the practical requirement is that the sand shall be as far as possible of uniform grain size. Typical sieve analyses for silica sands suitable for use with magnesium are given in Table 7.

TABLE 7

Typical Magnesium Moulding Sands.—Sieve Analysis

Retained on sieve mesh number	Bedford	Congleton	Parishes
16	0·52	—	—
22	2·3	—	—
36	25·75	1·5	0
44	27·15	8·5	2·0
60	36·55	27·5	19·5
100	7·9	49·5	75·5
150	0·5	12·0	2·5
200	0·1	0·5	0·2

Bedford sand is quite widely used but sometimes where surface finish is important, Parishes sand which is finer may sometimes be used as a facing sand with Bedford for backing. As can be seen from the sieve analysis, Congleton sand has intermediate properties.

It will be remembered that moulding sands for magnesium alloys were discussed from the aspect of suitable physical characteristics. These characteristics are necessary for the achievement and maintenance of high permeability. Oxidation of the molten metals in the mould was prevented by the addition to the sand of reaction restrainers or inhibitors.

The amount and type of inhibitor chemical used varies considerably with the type of casting and personal choice. A mould cavity requiring 100 lb. of metal to fill it will need a greater inhibitor content in the sand than a mould to produce a casting of a few ounces weight, for the reason that a greater volume of metal requires to be protected. Again, the average cross-section dimension regulates the amount of inhibitor addition; thin sections produced by narrow mould cavities will not require so much inhibitor in the sand as in sand facing a section of extreme thickness.

It may be suggested that a lesson might be learned from present American sand casting practice developed during the war to use women labour. In order to achieve foolproof standardization of method, one American foundry at least produced aircraft engine cylinders in what might be described as composite moulds. Different sections of the mould were made by the use of sand of specific properties, so that the factors of solidification rate and ease of production might be definitely observed. This suggests that moulds for magnesium moulding may be produced from sands containing varying amounts of inhibitors; for example, sand forming the cavity of a massive section could be higher in inhibitors than the sand to make a thin section of the same casting.

There is a good reason why this method should be adopted. Inhibitor contents should be the least possible to secure oxide free castings, for a major increase in inhibitor content may mean that the margin soundness and unsoundness may be small, especially in thin section jobs and in those cases where permeability is decreasing. Absence of inhibiting substances gives rise to what has come to be known as 'sand attack', in which it appears that a combination of molten magnesium, steam and the silica of the sand results in a chemical reaction with the production of unsightly defects on the surface of the casting. Inhibitors are added to core sand mixes also, and although it is problematic as to the amount remaining after baking, it is certain that the residual trace assists in the production of castings of good cored appearance, while complete absence of inhibitors in cores may result in some sand attack, not, of course, due to moisture from the core itself but possibly indirectly from the dilution of inhibiting gases within the mould.

In English practice it may be stated that magnesium moulding sand contains either sulphur and boric acid or ammonium bifluoride (ammonium acid fluoride); for castings up to 25 lb. weight, sulphur

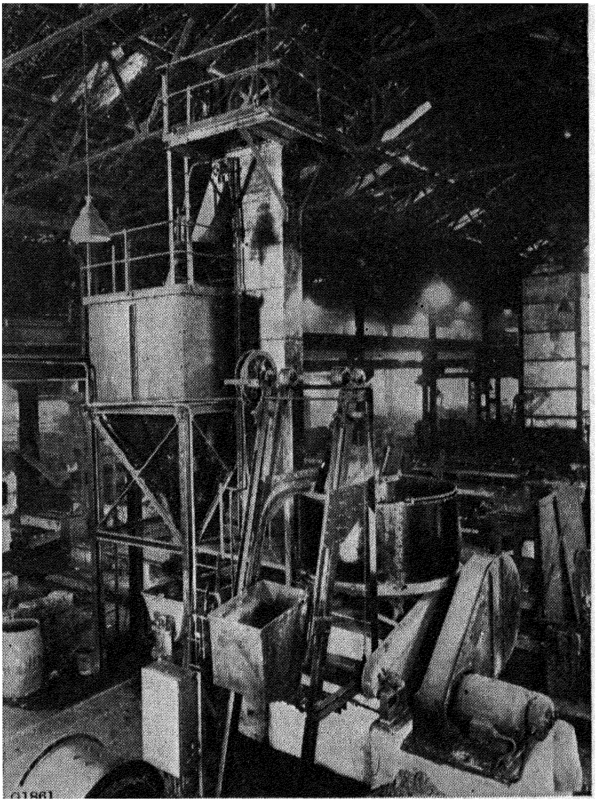


Fig. 11. Large mechanized sand conditioning plant used in a magnesium foundry. (*Pneulec Ltd.*)

and boric acid content of approximately 4 per cent and 1 per cent respectively have been found to be adequate. When the weight materially increases above this figure, it may be found necessary to increase the sulphur content, about 8 per cent being the maximum figure for the largest casting at present in production. The fluoride sands contain between 1 per cent and 3 per cent of ammonium bifluoride; with increase of bifluoride content above the latter figure, the moulding properties of the sand become very poor.

A typical mix in British practice would consist of:

Silica sand	100 lb.
Bentonite	4 lb.
Boric acid	1¼ lb.
Sulphur	4 lb.
Water	4 pints

The constituents are added in the order given and mixed until the 'feel' of the sand indicates that it has the correct cohesion. It should then be checked for moisture content and permeability should be around 120–150 A.F.A.

American practice tends to favour a mix of the following composition:

Silica sand	100 lb.
Bentonite	4 lb.
Ammonium silicofluoride	2½ lb.
Sulphur	1½ lb.
Boric acid	1 lb.
Diethylene glycol	1 pint
Water	3 pints

Magnesium moulding sand is prepared by mixing washed silica sand of the required grain size distribution and the inhibiting substances. Bentonite is added and water slowly added to the mix to hydrate the bentonite to form the clay bond. The moulder speaks of the 'feel' of the dry sand, by which, of course, he means his assessment of the moulding properties as made by inspection of the cohesion of a handful of sand. The amount of water added will be 2·5 per cent to 4 per cent to give a result that the moulder knows can be used. The permeability of magnesium sands so mixed, using the normal grades of silica sand, is 90 to 140 on the A.F.A. scale.

The period during which the prepared sand may be used is limited, for the artificial addition of water to a dry clay substance seems to give a clay having different properties from the natural clay associated with natural sands. The water seems to be more loosely held, with the effect that the sand, low in moisture at the outset, speedily becomes dry to the moulder's touch, and, in fact, unusable. This dryness is a real disadvantage in the use of synthetic sands, but a method has been previously suggested by means of which such dryness may be remedied.

Core Sands

Cores for magnesium sand castings are produced from similar synthetic sand mixes as indicated above, inhibitors being added although some of the amount would be lost during baking. A coarser base sand may be used with advantage, especially when the core makes contact with the moulding box face; in this way the maximum permeability is used with the certain evacuation of the mould of air, moisture and gases as the molten metal fills the mould cavity.

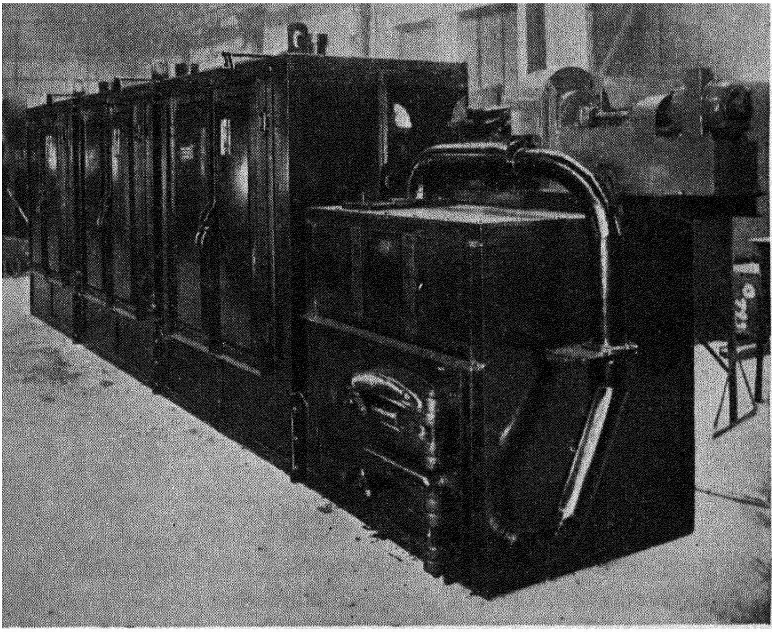


Fig. 12. Multiple coke fired core oven for baking sand cores.
(*Modern Furnaces and Stoves Ltd.*)

Cores for magnesium sand castings, however, require probably more care and consideration than those used for the sand casting of other non-ferrous metals. This is due to the chemical and physical characteristics of the solidifying alloy mentioned several times previously. It is, particularly, the physical properties of the metal which chiefly govern the required properties of a core, for immediately following complete solidification, the metal possesses little mechanical strength. It is essential, therefore, that no resistance shall be offered by the core to the contracting casting, and the ideal core would be one which commences to break down with certainty at some temperature about 450°C. (842°F.). Core mixes produced on the lines of those required for other non-ferrous metals should be materially modified to achieve success in magnesium alloy sand foundry production.

There are many appropriate core mixing compounds, consisting of dextrine and oil or combinations of these substances, on the market. They appear to have been elaborated to give satisfactory green strength, together with economy in baking time to achieve satisfactory dry strength. The sand used as a basis for cores may to advantage be of coarser grain than the moulding sand, and small amounts of inhibitors are added. The inhibitor content suggests another reason why temperature of drying should be kept to a minimum, usually about one hour at 150°C. (300°F.) will be adequate, for otherwise a large proportion of it will be lost due to volatilization. Indeed, it has been questioned whether inhibitors are required in a core mix, but it may be accepted that the small residual amount after baking is desirable.

A typical core mix would consist of:

	lb.
Silica sand	112
Sulphur	0·5–2·0
Boric acid	0·25–1·0
Dextrine/Cereal	0·5–1·0
Core oil	1·0–2·5
Water	6·0–8·0

In some mixes bentonite may be used either to replace the cereal binder or supplement it. The cores when dry should have a permeability of 150–190 A.F.A. Some foundries use a concentrated solution of ammonium bifluoride or ammonium silicofluoride sprayed on as an alternative inhibitor. Another mixture used which also improves surface finish consists of:

Industrial alcohol	1 gal.
Talc	1½ lb.
Boric acid	¾ lb.
Ammonium borofluoride	6 oz.

This is sprayed on the warm cores, usually after baking, and the coating allowed to air-dry.

Much work is being done in the United States and in this country at the present time on the use of synthetic resins for binders. It is stated that the action of these resins depends upon the action of heat giving a finally hard, infusible, and insoluble solid which bonds the grains of the sand. Once the hardening reaction has taken place the change is permanent.

Normally, cores containing the usual core oils become bonded on heat by reason of oxidation of the oil. The reaction is not complete unless all the oil is oxidized and, in practice, this may be difficult to achieve in production batches. There is often cause for complaint between the properties of cores from one batch to another. With the synthetic resins suggested, however, the change is one which does not depend upon oxidation; it would appear, therefore, that cores of more constant properties could be produced by their use. The synthetic cores achieve a maximum strength at comparatively low temperatures between 300°F. and 400°F., the time of stoving being materially reduced. Synthetic resin cores break down quickly at the temperature of molten magnesium alloys for the resin product decomposes at this temperature: the bond is thus destroyed. The casting is very easily 'knocked out'. Moreover, the core sand may be used again, with, of course, the addition of the original amount of resin. The resins used are known as urea formaldehyde plastics and are soluble in water. A successful mix is stated[10] to be as follows:

Core sand	100·0
Fly ash	4·0
Sulphur	1·0
Boric acid	1·0
Water	5·0
Urea plastic	1·0

(All the ingredients in parts by weight.)

Shell Moulding

Much interest has been shown in the possible applications of shell moulding to aluminium and magnesium foundry technique. Whilst a discussion of the advantages and limitations of the process are not within the scope of this book there is no doubt that this method of producing castings has become one of the accepted methods for producing castings. Shell mouldings can enable castings to close tolerances to be produced at a high rate of output and a low ratio of materials handled to castings produced. Whilst gravity die-casting limits the field of application the process has applications for certain classes of work and can sometimes be used to advantage for producing sand cores, especially where they are used in conjunction with a gravity die or where their shape makes them more economical to produce by this method.

The main development work on this process has been carried out in the U.S.A. Work carried out by the Dow Chemical Co. for the U.S. Army Ordnance Corps[11] has provided the main basis for a suitable technique. Although moisture is virtually absent from the mould magnesium will still react with silica in the sand tending to reduce it to the metal, and it will also oxidize in the presence of air in the mould. Suitable shell moulds can be made by mixing with the sand 0·2 per cent paraffin as a wetting agent and then 5 per cent of a phenol-formaldehyde resin and a suitable inhibitor. Boric acid appears to be unsuitable as an inhibitor added to the mix prior to curing but effective as a mould wash applied to the baked shell. Ammonium or potassium borofluoride is recommended both as an inhibitor incorporated in the sand mix (about 0·5–2·0 per cent) and as a mould wash; sulphur can also be added to the sand.

Due to the high strength of the shells it is preferable to use a urea-phenol-formaldehyde or furfural-phenol-formaldehyde bonded mix for cores since they have a lower retained strength and easier knock-out properties. Using a 5 per cent resin content cores can be produced from a core blower with an air pressure of about 30 lb./sq. in. and a contact time of about 30 secs. to 1 min., or the dump box technique used for moulds may be employed where the shape is suitable, in which case the dwell time will usually be shorter.

Investment Casting

This method has become important as a means of producing small intricate components mainly in specialized high temperature or wear resistant alloys. In the magnesium foundry it can enable small intricate parts to be produced economically in small to medium quantities. Investment moulding means that the component requires no parting lines since the components are made by injecting wax into a die and assembling the pieces on a suitable runner and adding feeders where necessary. The whole assembly is placed inside a steel box or tube and an investment slurry is poured around the pattern, vibrated to remove air and compact the mould, and then allowed to set. After drying out the mould is removed from the container, the wax melted out and the final traces of wax burnt out at 650°–750°C., after which it is cooled to around 150°–350°C. for casting.

For magnesium investment casting a mixture of plaster of Paris and silica has been used with a silica content of around 10–25 per cent. However, there is a tendency for magnesium to react with this mixture. American work[12] suggests that the additions of aluminium fluoride to the plaster investment and removal of air from the mould, presumably by flushing with sulphur dioxide gas, will enable satisfactory castings to be produced.

REFERENCES

[1] British Patent 187,943.

[2] British Patent 219,753.

[3] British Patent 287,164.

[4] U.S. Patents 1,895,639 and 1,917,759.

[5] N. B. PILLING and J. D. BEDWORTH. *J. Inst. Metals* (1923), **29**, 529–5.

[6] R. DELAVAULT. *Etude des Phenomenes Superficiels dans l'Oxydation de quelques Metaux Fondus.* Doctorate Thesis (1936), Centre de Documentation Universitaire, Tournier et Constans, Paris 5e.

[7] A. SCHNEIDER and U. ESCH. *Z. Metallkunde* (1940), **32**, (6), 173–7.

[8] M. E. GANTZ. *Magnesium Foundry Sand Practice.* A.F.A. Reprint 43, 36, p. 73.

[9] F. A. ALLEN. Magnesium Moulding Sand. *Light Metals* (1947), **10**, (110), 120–3.

[10] ANON. Using Synthetic Resin Core Binders. *Foundry* (1945), **64**, 198.

[11] ANON. Shell Moulds for Magnesium Castings. *Machinery* (*Lond.*) (1953), **83**, (214), 1069–70.

[12] P. BUTLER. Magnesium Investment Castings. *Modern Metals* (1952), **12**, 69–70; see also *Light Metals* (1953), **16**, (178), 26.

CHAPTER 5

Production of Sand Castings

BEFORE CONSIDERING the main types of running and feeding methods used on magnesium alloy castings it is again necessary to reconsider the basic physical and chemical properties of the metal. In the first place its pronounced tendency to oxidize will strongly influence the type of sprue (downgate) used. Secondly the size of the risers will be determined by the density of the metal, its thermal properties and solidification range. Finally the disposition of gates will be influenced by the factors already mentioned and by the necessity of obtaining the most favourable temperature gradients so that those portions of the casting which are the last to solidify can still be fed with molten metal.

The physical properties of magnesium compared with other common metals is given in Table 8.

TABLE 8

Thermal Properties per Unit Volume of Magnesium Compared with Other Metals.[7]

Metal	Specific Gravity	Mean Specific Heat		Latent Heat of Fusion (cals./cm.^{3})
		Solid	Liquid	
		cal./cm.^{3}/ °C.		
Magnesium	1·8	0·50	0·54	90
Aluminium	2·7	0·68	0·70	250
Copper	8·9	0·89	1·06	440
Iron	7·8	1·25	1·34	500

These values show clearly that in the first place magnesium is much lighter than any of the common metals, being even a third lighter than aluminium. This means that to produce the same hydrostatic (liquid) pressure in the risers for feeding a correspondingly larger volume of metal is required in the risers. In addition, the low specific heat and latent heat of magnesium, whilst it means that less heat is required to melt the metal, results in magnesium castings tending to solidify more quickly which also increases the difficulties of feeding.

Determination of Optimum Casting Conditions

Various investigations have been made into the conditions which contribute to the production of sound magnesium castings. A useful general review of the factors contributing to the making of good castings in all metals has been made by Ruddle.[1] In relation to magnesium the work of Chamberlin and Mezoff[2] is of particular interest since they measured the temperature gradients in ¾-in. thick magnesium plate castings made in Dowmetal H (6 per cent Al, 3 per cent Zn). These castings were made using various moulding and chilling materials so as to obtain different rates of solidification. The temperature gradient measurements were correlated with the mechanical properties of the castings and it was established that for optimum strength and soundness a large favourable temperature gradient—about 50°C./in.—was essential.

The importance of temperature gradients in influencing soundness has been well demonstrated by Baker[3] who made temperature gradient measurements on bottom-run top fed, 1-in. dia. bars in several magnesium alloys. He demonstrated that under these conditions of casting the temperature gradients are extremely unfavourable since the bottom of the casting is hotter than the top. Eventually the position changes as solidification proceeds and the gradient is reversed at some point between the metal commencing to solidify and the completion of solidification. This is also confirmed in the investigation of Ruddle[4] on temperature gradients in a 10 in. × 5 in. dia. cylinder on a 9·8 per cent Al alloy where similar measurements were made.

The shape and section thickness of the casting obviously influence these temperature gradients. Experiments made by Eastwood and Davis[5] on casting of plates 10 in. × 6 in. and between $\frac{3}{16}$ in. and 1½ in. thickness showed that the $\frac{3}{16}$-in. plates and the 1½ in. thick plates were the most difficult to make sound. The thin plate obviously presents problems because the thin section solidifies quickly and it is difficult to obtain a temperature gradient adequate to promote feeding. With the thick plates the reverse conditions will be encountered and the problem is one of retaining enough liquid metal in the feeder to supply metal to the last sections to solidify. Alloy composition affects such behaviour, the alloys having a high eutectic content being less susceptible to shrinkage porosity.

The factors reviewed above have much practical importance. Since magnesium is reactive in the molten state it is axiomatic that the metal must enter the mould smoothly and continuously so that the channels are kept full of metal. In order to promote favourable temperature gradients bottom pouring is used but it is often easier to secure a smooth flow of metal filling the mould by use of an up-sprue slit gate. The risers will be much heavier than for other metals, even aluminium alloys.

Running and Gating Systems

We may now consider in more detail the points to be observed in deciding the running and feeding system to be used for any magnesium casting. It will be essential to ensure that oxidation of the metal is kept to a minimum and that as far as possible oxide should not enter the casting. The metal stream from the sprue should not enter the mould cavity directly but through a gate. If the gate is taken off at an angle to the main flow of the metal a degree of physical separation of the oxide is achieved, sufficient for most purposes. With large thin walled castings more elaborate separation may be needed and this can sometimes be achieved by means of a whirl gate (*Fig.* 13). This device aims to produce a quick rotational movement of the molten metal so that the oxide is separated mechanically. Provided there is adequate inhibitor in the sand and some sulphur is dusted on the molten metal during pouring the oxide is not carried over into the casting.

Another popular method is the use of a sprue made up of a series of slits fed from a pouring cup (*Fig.* 14). With a deep mould the breaking up of the metal stream tends to produce a vortex in a round sprue and this avoids turbulence and oxidation in the sprue. This type of sprue has often been used in conjunction with a filter of steel gauze placed in the runner, and in the United States use is made of a tubular fine steel mesh screen placed in an up-sprue slit gate to achieve the same effect. An alternative practice is to break the flow of the metal stream at a mould joint. The bottom of the sprue should be rounded and lead smoothly into the runners. Triangular-shaped runners with the corners slightly rounded are preferred since they keep the exposed metal surface to a minimum and assist the flow of metal. Flat, slot runners have been shown to reduce metal flow as compared with circular runners[6] and should be avoided when thin-walled castings have to be produced.

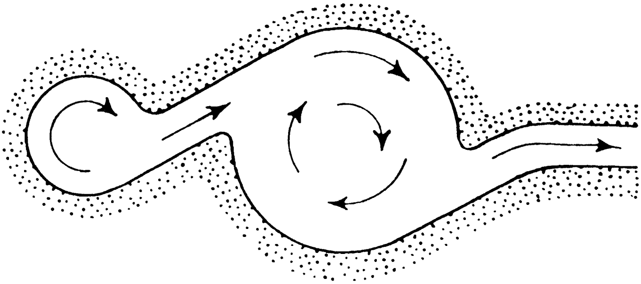


Fig. 13. Whirl gate showing paths of metal flow.

It is important to ensure that the cross-sectional areas of the sprue, runners and gates are of such proportions that they remain full during pouring. Runners should be tailed off so that the first metal poured will not enter the casting cavity but any oxide, sand or other impurities washed before it will be carried into the ends of the runners. The gates should be positioned a little distance back from the ends of the

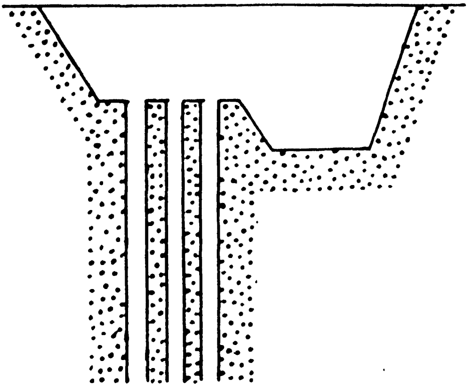


Fig. 14. Diagram of slit gate such as is frequently used for magnesium castings.

runners and inclined away slightly from the main metal stream. With many large flat castings bottom gating is often preferred although this may involve the production of cores to produce the appropriate shaped gates.

An example of the application of bottom gating is shown in *Fig.* 15, which is a relatively thin-walled box-type casting about 2 ft. × 1 ft. 3 in. × 9 in. On account of its size and the need to fill the mould quickly double pouring has been used, two slit sprues carrying the metal to the corners of the mould cavity. A slit gate and riser provides a satisfactory means of ensuring that the hottest metal is kept at the top of the mould. When full the slit gate device becomes a riser for feeding the casting.

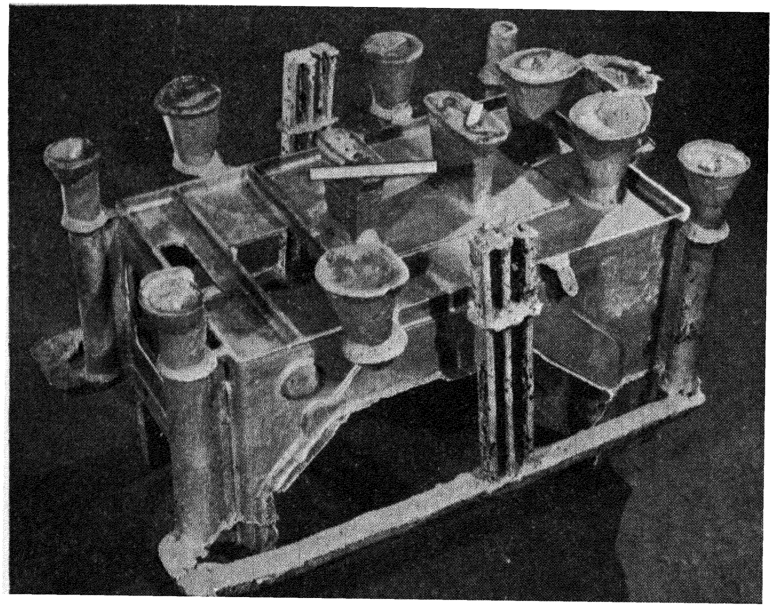


Fig. 15. Box-shaped casting incorporating slit sprues with bottom gating. (*High Duty Alloys Ltd.*)

Small ring-shaped castings can be simply produced by using a ring gate and placing small top risers, equally spaced on the periphery as shown in *Fig.* 16. The side risers are there to feed a heavy section on

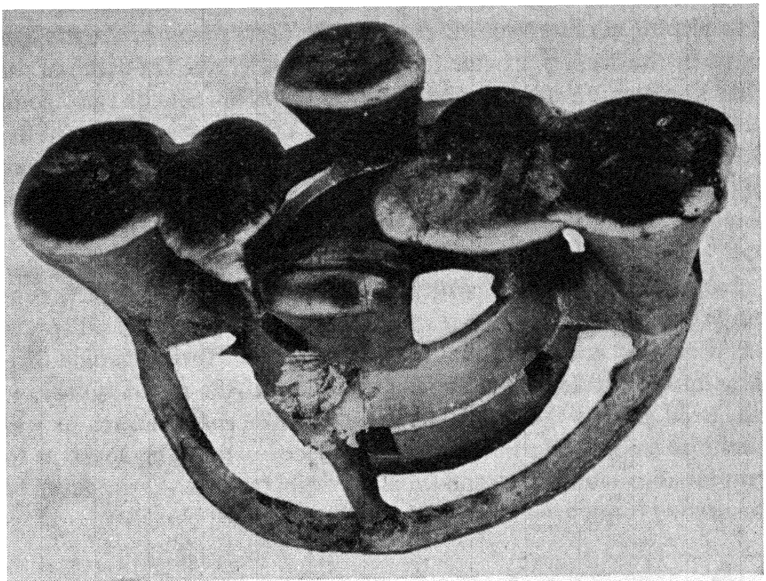


Fig. 16. Running system for small ring-shaped casting.

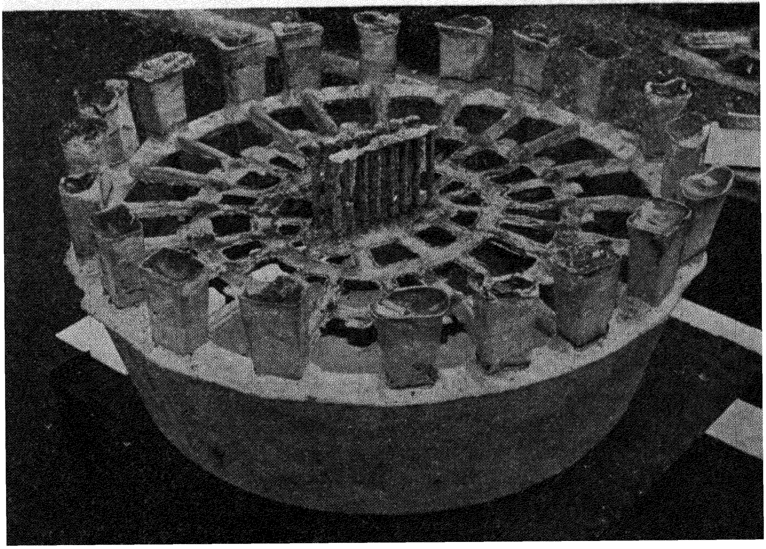


Fig. 17. Large thick-sectioned ring casting with runners and risers.
(*High Duty Alloys Ltd.*)

the interior face of the ring which cannot be seen in the photograph. The placing of these two side risers on the outer circumference is dictated by the need to provide for easy fettling. Where the depth of the ring is greater it may be necessary to place the ring gate on the second parting line at the base of the casting and a further ring runner at the first parting line to supply hot metal to the risers and to break the fall of the metal and thus reduce turbulence. The downright should therefore not be in the same position on the lower half as in the top half.

Large, thick-sectioned castings require care in arranging the running system. One approach is shown in *Fig.* 17. A series of slit sprues has been used and then a series of radial runners formed which then flow into a circular ring. The continuation of the radial runners is staggered so that the flow path is broken in a manner such as will minimize turbulence. Large risers are placed over each gate so as to provide adequate feeding and keep hot metal in them. As the depth of the casting is not great there is no need to use a slit gate.

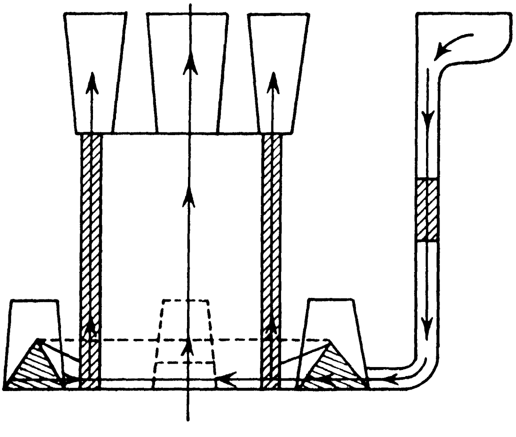


Fig. 18. Bottom gating method for making tall cylindrical casting.

Where deep cylindrical castings are necessary bottom pouring is often resorted to. A conventional method for moulding such castings is shown in *Fig.* 18. However, the large volume of metal flow through the three gates results in much heating of the mould around these areas and generally speaking the bottom of the mould will be hotter

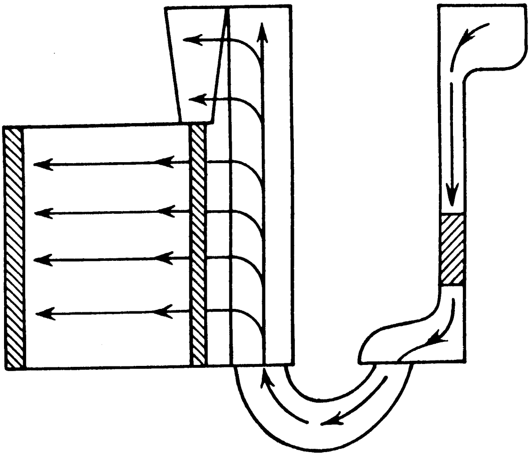


Fig. 19. Slit-gate system for running tall cylindrical casting.

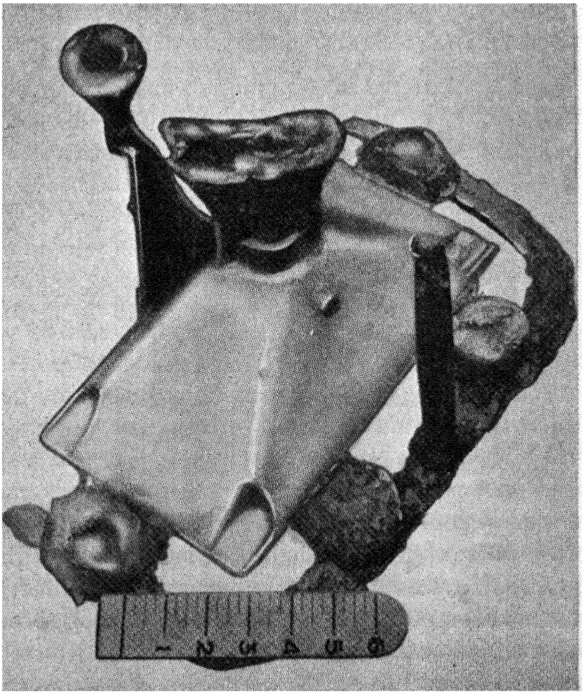


Fig. 20. Running system for small thin-walled casting incorporating blind risers.

than the top. Although it is possible for the temperature gradients to readjust themselves favourably before solidification is complete, with either thin walls or very thick ones, in relation to the depth of the casting, this may not occur and the casting will be unsound. An alternative and more favourable approach is that shown in *Fig.* 19, where a slit gate is used so that hot metal moves up the mould as it fills and the hot spot is confined to around the gate and feeding becomes a simple matter.

These walled castings of the type used for covers or casings on instruments are commonly encountered. In producing these every care should be taken to give the maximum possible assistance to the metal to enter the mould cavity and thus keep the casting temperature to a minimum. Where there are small bosses or ribs near the periphery these can often be fed through small blind risers. An example of a running system of this type is shown in *Fig.* 20. This arrangement makes for ease of fettling and economy of metal.

Chills

Where chills are required in sand moulds cast iron or aluminium pieces will be used. Generally speaking aluminium chills will be about 50 per cent greater in thickness than is required for cast iron because of the former's lower heat capacity. Aluminium alloy chills are often favoured in the light alloy foundry because they are more readily available and special shapes required for any given job can be cast on the spot. In any case such chills will require a coating to protect them from any possible reaction including alloying with the molten metal. A suitable wash which can be used consists of:

Industrial alcohol	2¼ gals.
Talc	10 lb.
Truline rosin	1 lb.

The rosin is an alcohol extracted rosin and is much preferred to ordinary rosin. The chills can be allowed to air-dry but preferably such be ignited with a torch. An alternative mixture is that given as a core wash mixture on p. 63 in which boric acid and borofluoride have been incorporated instead of rosin, thus also rendering it suitable as a mould dressing.

Another mixture which can be used, and which has also been used on moulds prior to skin drying, is that described by Tedds.[8] The basic mixture consists of:

Ethyl silicate	2½ pints
Hydrochloric acid (0·5 per cent soln.)	½ pint
Water	7 pints

The hydrochloric acid is added to the ethyl silicate and both are well mixed and allowed to stand for 15–30 min. during which the temperature may rise to 50°C. The water is then added and the whole thoroughly mixed. After cooling to room temperature suitable refractories, such as fine Molochite sand, or alumina or sillimanite, are added to give a consistency suitable for dipping, brushing or spraying. An inhibitor is also often incorporated.

The examples given in the foregoing description of typical castings and the moulding methods employed served to expand the basic principles discussed in the opening paragraphs. At the risk of being unduly repetitive these can be briefly recapitulated. When developing a magnesium running system every care should be taken to avoid turbulence. The metal should never be poured directly into the mould but first into a pouring basin. Never let the metal stream run directly into a mould, always use gates positioned out of the direction of the metal stream. Wherever possible bottom pouring is preferred but a slit gate will often assist in producing a good distribution of heat so that the last part of the casting to solidify can be fed with hot metal. Heavy risers should be used at points where they are most needed but they cannot always rectify bad distribution of temperature in the mould. Once a technique has been established, details should be recorded and the method standardized.

Following these principles it should not be difficult to assemble a mould which would enable a sound casting to be produced. However, the satisfactory production of sound castings depends upon careful observance of small details particularly in casting. When the mould is finally closed prior to pouring the sprue and runners should be kept covered until ready for pouring to avoid the possibility of foreign matter or dust entering the mould cavity. If the volume of the mould cavity is large it may be desirable to flush the mould with sulphur dioxide gas to prevent oxidation. Although this is not necessary for small castings it is desirable on large ones.

Care should be taken not to contaminate the risers with sand. There is a tendency for foundry personnel to cover the top of the mould with sand shortly after casting with a view to reducing the amount of sulphur dioxide reaching the foundry atmosphere. This often results in sand being trapped in the partially solidified metal with the result that the silicon content of the next batch of castings rises due to the reduction of the silica in the sand caught in the risers to the metal—silicon—when the foundry scrap is remelted. The better remedy is to arrange for either adequate exhaust hoods over the moulds or their removal to a well constructed cooling tunnel.

Trimming and Dressing

Castings must not be removed from the mould too quickly since they will distort when hot; the temperature should preferably be less than 300°C. After cooling, the castings should then be sent for fettling. Runners and risers are most readily removed with a bandsaw; one with 4–5 teeth per in. with the set of the teeth 0·020–0·032 in. on either side to provide clearance is preferred. Cutting speeds of 5,000–8,000 ft./min. are normally used, and no lubricant is required. For grinding operations proprietary wheels are available which are specially developed for use with magnesium alloys. A coarse grit of 40–80 mesh is preferred and the bond should not be too strong or inflexible, a softer binding agent is preferable. Peripheral speeds will be in the order of 3,000–10,000 ft./min., but the type of bond used will normally be the determining factor in deciding the speed to be used. High-speed routers have also been very successfully used for special work. Where hand files are required they will be of the coarse 'millencut' type.

The dust produced from sawing and grinding operations constitutes an explosion hazard, as is the case for most finely divided materials. In different countries there is legislation in existence designed to ensure observance of minimum precautions to avoid danger. Essentially all of these methods depend upon extracting dust at its point of origin and suppressing it by mixing it with water, or in some cases oil. Efficient extraction of the dust combined with regular sweeping of the shop will eliminate any risks on this account. There is also a fire hazard with magnesium dust but provided tools are kept sharp and glancing blows avoided on other metals such as steel, which could be the source of a spark, then the danger is negligible.

Magnesium, if struck a heavy blow with steel, could also be the source of a spark.

To conclude this chapter it may not be out of place to deal with the subject of rectification of magnesium alloy castings, for in spite of the careful control that has been emphasized throughout, defects such as mis-running or non-running in small areas do occur at times. Naturally, the foundryman is loth to agree to scrapping such castings if they may be repaired by a simple process. The application of rectification is strictly governed by official regulations with regard to stressed aircraft castings, but for unstressed commercial work the only guide is based upon the discretion of the Inspector.

The process consists of cleaning the area of the defect by scraping or filing, the cleaned cavity being tapered outwards. It is essential to pay careful attention to this preparatory cleaning operation or otherwise the weld will be unsatisfactory. The cavity is then surrounded by floor moulding sand so that when molten alloy of the same composition as the casting is poured it will flow into the cavity, and further overflow into a sump also made in the temporary mould. Metal is poured from a small pot or ladle at a fairly high temperature as the surface layer of the hole has to be melted to weld up satisfactorily with the new metal. Sometimes the cavity is puddled with a wire to assist in the welding process. The casting, when cool, is separated from the temporary mould and then fettled and finished in the usual manner.

The degree of inspection applied to the repair will largely depend upon the use to which the casting will be put ultimately. The minimum inspection should be visual to make sure that the weld is satisfactory and that there is absence of cracks which may be caused by unequal stresses due to the necessary application of heat. It is therefore desirable to subject castings required in the as-cast condition to an annealing treatment, and those castings required in a heat-treated specification to a second heat treatment if the welding has been performed at the conclusion of the normal manufacturing process.

It must be pointed out that the weld metal, even although it is of the same composition as the original metal, is sufficiently different in properties to be revealed by X-ray examination or by chemical treatment, such as the chromating process. Although rectification can be performed satisfactorily it should, however, be the policy of both production foundry and inspection to guard against any tendency to use the process too easily, for the occurrence of similar defects should be regarded as being symptomatic of incorrect process requiring investigation and subsequent remedial action.

REFERENCES

[1] R. W. RUDDLE. *The Solidification of Castings.* Institute of Metals, London (1950).

[2] M. V. CHAMBERLIN and J. G. MEZOFF. *Trans. Amer. Found. Soc.* (1947), **55,** 66.

[3] W. A. BAKER. *J. Inst. Metals* (1945), **71,** 165–204.

[4] R. W. RUDDLE and A. L. MINCHER. *J. Inst. Metals* (1950), **178,** 229–57.

[5] L. W. EASTWOOD and J. A. DAVIS. *Trans. Amer. Found. Soc.* (1946), **54,** 254.

[6] J. G. MEZOFF and H. E. ELLIOTT. *Trans. Amer. Found. Soc.* (1948), **56,** 279–84.

[7] E. A. G. LIDDIARD and W. A. BAKER. *Proc. Inst. Brit. Foundrymen* (1944–5), **38,** A69.

[8] D. F. B. TEDDS. *Proc. Inst. Brit. Foundrymen* (1949), **42,** A120–6.

CHAPTER 6

Gravity Die-Casting

FOR SOME YEARS the casting of aluminium into metal dies has been an established art. The more widely used method in Great Britain has been that of gravity die-casting referred to in North America as permanent mould casting. It is also widely used for the production of magnesium castings and for the same reasons, namely higher dimensional accuracy and rate of output with lower cost. Pressure die-casting is also well established and will be referred to later.

Fundamentally, of course, the same principles apply as in the die-casting of other metals, the general rules of production and planning depending upon the economic considerations of the quantities ordered. There are, in addition, advantages of die-castings over sand castings; the machining costs are less as the die-castings can be produced much nearer to finished size and with a much more pleasing surface and saving of metal than sand castings. There is improvement in the mechanical properties due to the rapid solidification of the molten metal and the resultant fine grain produced. Any special technique which has to be employed arises, as in sand casting, from the chemical and physical properties of magnesium, special precautions being taken to prevent turbulence and excessive oxidation and burning; such factors having an effect upon the melting and pouring technique, and, to a lesser degree, on the actual method of running and feeding the casting embodied in the die.

It is absolutely essential for magnesium alloys to have 'hair trigger' dies, that is, dies which will operate very smoothly and very quickly, as, apart from the production being easier and less fatiguing to the operators, many magnesium alloys are prone to hot shortness and if the casting is allowed to remain in the die but slightly longer than necessary cracking will inevitably occur. If allowed to remain still longer, the casting will be found to contract on to the die and the greatest difficulty will be experienced in removing it, it being more than likely that the die will be in need of repair.

Fundamentals of Die Design

Although, broadly speaking, the fundamental requirements for the running and feeding of gravity die-castings are the same as those followed in sand casting, the location of the runners and risers for the purpose of producing a sound gravity die-casting is something which demands much thought. The foremost aim of a well designed runner is to produce a quick smooth flow of metal into the die and for this purpose many types of runners have been devised, the type employed depending of course upon the size and shape of the casting. Permanent moulds possess an advantage in obtaining a smooth flow of metal over the sand mould in that they can be tilted, especially in the case of small castings.

Allowance should be made when producing the die that any minor modifications to these runners which become apparent when the die is tried out in the foundry may be easily and economically effected. It will be found that with careful planning and the allowance of generous fillets and radii in those parts of the casting which would appear from experience to be the parts most liable to cracking, little trouble will be experienced from this source. The risers used to feed die-castings are not so large in proportion as those used in sandcasting.

The design of dies is not merely an engineering job involving machining of a metal block and its conversion into a workable die but an art requiring the practical knowledge of the foundryman on casting methods, some knowledge of metallurgy and the ingenuity of the tool maker and mechanical engineer. It is probably true that the most successful die foundries are those in which die design is controlled by a foundry superintendent who has a sound practical engineering background with tool-room experience but having also gained experience in foundrywork.

The materials used for the manufacture of gravity dies will depend upon the quantity of castings which may be produced from the die and the wear likely to be experienced on any individual piece. For small to medium quantities, the main die blocks will usually be made in a low phosphorus cast iron or a nickel-chrome cast iron. The following is a typical composition range:

	%
Total carbon	3·0–3·5
Combined carbon	0·4–0·5

Silicon	1·6–2·0	
Manganese	0·5–0·8	
Phosphorus	0·30 max.	
Sulphur	0·05 max.	
Chromium	0·6	optional
Nickel	0·2	
Molybdenum	0·4	

Where long runs are required or heavy wear occurs, it will be preferable to use a die-steel such as is used for pressure die-casting, although a low chrome-molybdenum steel such as one containing about 0·4 % C, 1·5 % Cr, 0·5 % Mo, 0·3 % V, will often prove satisfactory and is cheaper than chromium-tungsten or higher chromium-molybdenum-vanadium types common to these materials. For cores and slides mild steel will often prove satisfactory, although alloy steels again find use for the more arduous applications, e.g. pins. Blocks should be properly annealed before machining to ensure freedom from subsequent distortion.

Importance of Temperature Gradients

Some years ago it was accepted in most quarters that gravity dies should be as heavy as possible since the high heat capacity of the die would tend to make for uniformity of temperature. Experience has shown that this is by no means an essential requirement for the production of good die-castings, and may in fact be a decided disadvantage.

In the previous chapter we have referred to the importance of temperature gradients in the production of sound sand castings; often a temperature gradient across certain sections of the die will give the correct heat distribution required to give good die-castings which would be unobtainable by changes in running or gating. Adjustments to the angle of impingement of the gas flame on the die wall of minimum section will often be sufficient to achieve and maintain the desired temperature gradient. With thinner walled dies the lower weight of metal in them often means that the heat produced during solidification may even balance the loss of heat in the die by convection and conduction.

The whole question of die temperature is a complex one and only a few pointers are available to those without previous experience. There is probably a maximum operating temperature that can be achieved with any given die owing to heat losses inevitable in die-casting. It will often be found that the heat provided externally roughly balances that lost from various causes. Of course, by increasing the heat input over a given area, such as is given by the use of a higher pressure air-gas system, the temperature of the die can be appreciably increased but this usually leads to intolerable working conditions.

It is, of course, difficult to measure die-temperatures and to study conditions in die-casting in a manner which lends itself to scientific analysis. In some measurements made by one of the authors on a production die it was found that the die temperature fluctuated during the initial casting period between 260°C and 300°C. as measured in the period immediately prior to pouring and after some six to ten castings the temperature flattened out at around 235°C.

These tests were made on a relatively simple casting which could probably be produced satisfactorily over a range of die temperatures. However, many complicated castings will only be produced from the die in a relatively small temperature range which will be established by pre-production trials. Care will be necessary to ensure that full information is available to production personnel on the conditions of operating dies particularly where maintenance of a pre-determined die temperature is essential for satisfactory production.

The temperature at which the die works successfully in the experimental stage should not be determined in terms of a single temperature that will be almost impossible to hold in practice. It may occur that the range of permissible temperatures is narrow. Since it has been found that under some operating conditions the die temperature is likely to fall fairly rapidly, a point will be arrived at where scrap is produced; many dies have what might be called a time-temperature cycle. It may be sound economics to investigate the meaning of this in terms of the number of castings that can be produced within the cycle, and then cease production, to enable the die to be reheated to the higher limit of the temperature range.

From the point of view of production and efficiency, it is self-evident that it is better to produce ten good castings in forty minutes, than to produce a total of fifteen, of which five are scrap, in an hour. A scrap casting represents greater losses than die-caster's labour; it represents lost labour charges and melting loss during subsequent remelting.

Die-Coating

There are, however, well-known 'tricks' of the die-casting trade practised to achieve some control of the solidification process. Of first importance is the application of die wash, because it enables the flowing metal to lie quietly on the mould; also, of course, it protects the mould from excessive wear. Much may be done in solidification control by modification of the wash in regard to thickness of coat and type. If a wash having a refractory base is used, thickening the wash at certain areas will have the effect of delaying solidification quite appreciably at that part. At sharp changes of section it is customary to remove the wash altogether and so provide a chilling effect.

Washes having a graphite base have been used in which the thermal properties are markedly different from the more usual silicate washes. It may be suggested that die wash action is a promising line of industrial research, for it will be agreed that to a large extent the selection of a wash for a certain job is, at present, either completely haphazard or is the result of trial and error. If the successful operation of an expensive die depends to any extent upon the use of the correct die wash properly applied, it will be seen that this apparently trivial subject is, in fact, of major importance.

Most die-castings are sold as proprietary articles, and little published information is available on their composition. The following two mixtures, which have been used in production, are typical of those employing sodium silicate as the binding agent.

(1)	French chalk (asbestine)	1¾ lb.
	Sodium silicate	½ lb.
	Water	1 gal.
(2)	Kaolin (china clay)	2 lb.
	Sodium silicate	1 lb.
	Water	½–2 gals.

Where a smoother and softer coating is required, a wash containing magnesium oxide with boric acid as the binder can be used. A typical composition is given below.

(3)	Magnesium oxide	½ lb.
	Boric acid	½ lb.
	Water	1 gal.

An early German patent[1] covered the use of a dilute suspension of boric acid and precipitated chalk as a die dressing. French chalk can be substituted for magnesium oxide in mixture No. (3), whilst graphite can replace part or whole of the suspended matter in either of these mixtures. Where boric acid is used, the coating will be softer than those containing sodium silicate.

The viscosity of die coatings should be adjusted to suit the spraying equipment used and the thickness of coating required. This means that the casting cavity will normally be coated more thinly than the runners and risers, since a thick die coating tends to act as a heat insulator, thus increasing the efficiency of the risers for feeding. Where the higher thermal conductivity of a graphite wash is required, it will be logical to use two die coatings if the die is a large one. The graphite wash would be used in the die cavity, and a French chalk—silicate wash on the risers for heat insulation.

Some parts of the die are exposed to more wear than others and the life of the die-casting can be extended by dusting with a finely powdered mixture of boric acid and French chalk. The presence of boric acid in the wash helps to reduce oxidation of the castings especially in conjunction with sulphur which should be lightly dusted into the die when large castings are being produced. With some die parts, such as long cores and sliding pieces, graphite will be preferred as a local coating since its lubricating properties assist withdrawal of these pieces.

Melting Furnaces

Melting of metal for die-casting follows the principles described in Chapter 3, and some reference has been made to differences between British and American practice. Melting in the tilting furnace of the type shown in *Fig.* 21 is favoured in Great Britain. During transfer of the metal from the furnace to the die it is kept dusted with sulphur, the flux forming a firm protective crust on the melting pot.

An alternative melting furnace is the fully enclosed bale-out type which was patented by High Duty Alloys Ltd.[2] and subsequently introduced into the United States by the Dow Chemical Co. where it still finds favour, especially for pressure die-casting.

This furnace (*Fig.* 22) consists of a shallow melting pot similar inside to that used for aluminium die-casting with appropriate heating burners. A hood completely covers the pot except for a rectangular opening so positioned that a suitably sized ladle may be inserted into the molten metal. In the original H.D.A. furnace a flue was placed above the aperture, providing an upwards draft of products of combustion from the burners, thus sealing the metal from the atmosphere. Sulphur dioxide gas was introduced into the hood above the metal surface to maintain the inert atmosphere.

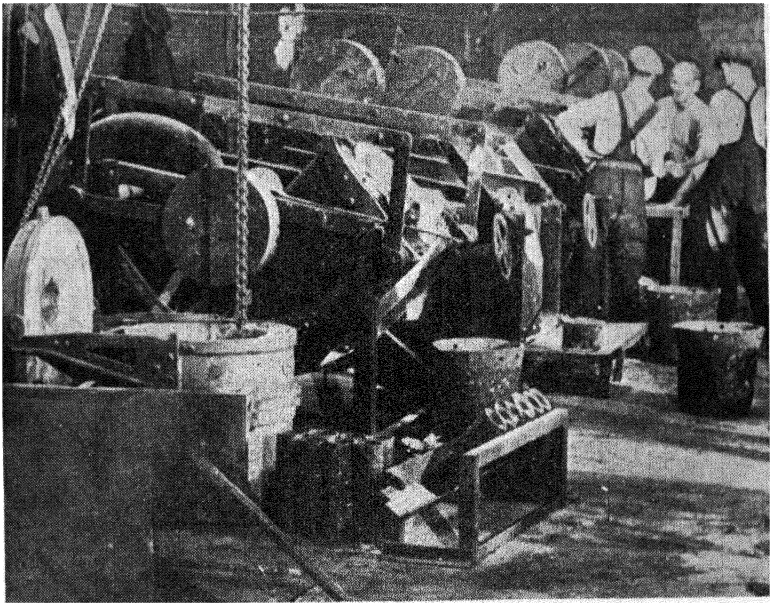


Fig. 21. Tilting furnaces used in magnesium gravity die casting.

American modifications to the design have led to the sulphur being held in a specially designed container placed over the melting pot into which compressed air is introduced at a very slight pressure, thus producing sulphur dioxide. The provision of the venture stack and exhaust fan prevents escape of the sulphur dioxide into the foundry. As indicated in Chapter 3 a specially formulated flux is desirable for use with this furnace, it being so designed that the surface is covered with a fluid flux which will sink to the bottom as it becomes contaminated. Regular removal of spent flux, preferably daily, is desirable for good operation and cleanliness of the metal.

The furnace design was only one part of the original patent, since a ladle specially designed for die-casting was also described. This ladle is hooded over half of the area including the spout end, which was actually an orifice of suitable size. A controlled rate of pour for any particular job was thus assured, which can be an important factor in the production of some castings particularly where casting temperatures and conditions are critical.

The hood over the ladle covers a sufficient area that where it is tilted during pouring it is higher than the pool of metal being poured. The sprinkling of sulphur or dusting powder on the metal surface enables complete protection against oxidation to be given to a much reduced surface area.

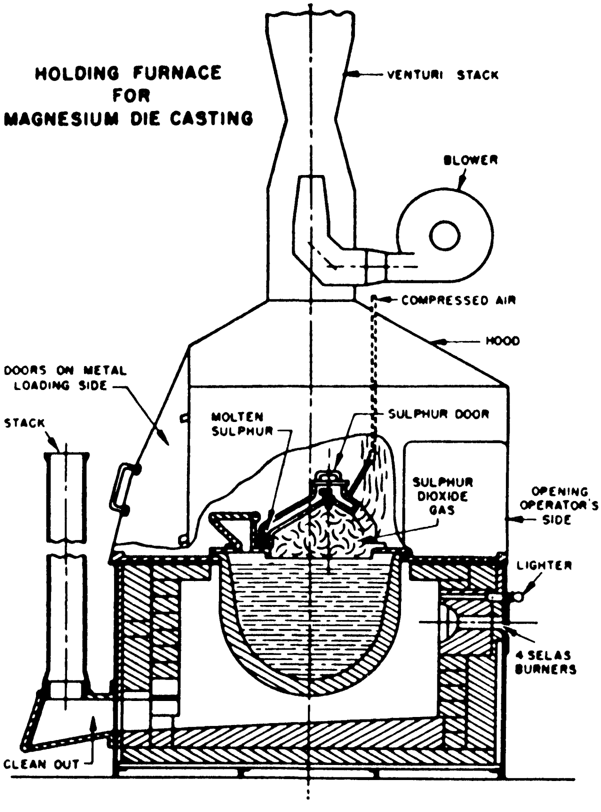


Fig. 22. Section through magnesium die-casting furnace based on High Duty Alloys Ltd., patent.[8]

Apart from the two types of furnace described above there has been used in the U.S.A. a shallow bale-out furnace which is operated in a manner similar to that used in gravity die-casting aluminium. The ladle pushes back the fluid flux cover prior to filling with metal, and on withdrawal the surface of the metal is lightly dusted with inhibitor to provide temporary protection for the very short period in which the flux cover is reforming. This method is very simple but there is rather more risk of flux inclusions and oxidation through careless operation than with the two methods previously described.

Melting for gravity die-casting is carried out in several large American foundries by melting in a large central furnace of around a ton capacity and this is used to supply the holding pots. The fluxing and refining of the metal is carried out in the holding pots prior to casting.

Casting Operations

An essential part of die-casting is the correct pouring of the casting and its extraction from the die. Pouring should be carried out smoothly so that the protective tube formed by dusting the stream with inhibitor is left unbroken due to pouring and the metal enters the die smoothly.

The size of the hand ladles used for pouring the die-casting depends upon its larger castings requiring two ladles or even more. They should be preheated to red heat and when not in immediate use must be kept hot. If this is not done, a damp ladle may be placed in the molten metal and result in an explosion with possible serious injury to the furnaceman, in addition to the fact that the metal might be excessively cooled and result in high metal loss by skins of metal sticking to the ladle. Sometimes special controlled pour-ladles are used to help the smooth flow of metal into the die and thus prevent or mitigate the effects of turbulence and severe oxidation. It is not essential to use a wash on these ladles but it will be found generally advantageous to coat them with a mixture of whiting or French chalk and water-glass. There are many other washes which may be used including proprietary compounds, but for general purposes the above mix will give ample satisfaction.

A sequence should be established for opening the die so that adequate time is allowed for solidification and cooling of the casting and the removal of cores and pieces in a manner least likely to give rise to distortion whilst the metal is still somewhat plastic. At all times it should be remembered that light alloys have little strength at high temperature, and therefore it is essential that the movable cores, ejectors and die sections should part easily and smoothly, if cracks and distortion are to be avoided. Bearing surfaces should be lubricated with graphite, and if cores require chilling on account of necessary high metal temperature or for the preservation of the correct temperature relationship, a graphite suspension should be used as the quenching medium.

Further to this question of casting withdrawal, it should be noted that maintenance of a vertical position for the casting is often essential, especially if massive sections are situated at the base of the casting. If the casting is held by tongs in such a way that it is hanging cantilever fashion from a riser the weight will often be sufficient to distort the body of the casting.

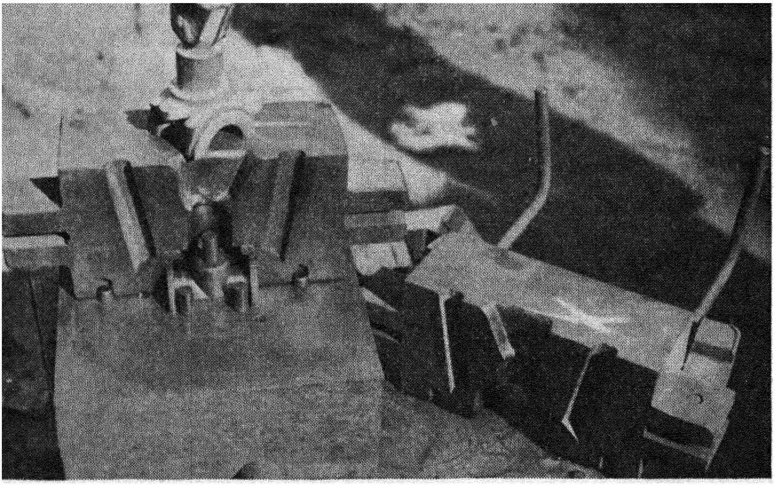


Fig. 23. **Small die and casting therefrom showing construction of die.**

Great care must also be observed in taking the casting from the die. It is preferable to place the castings in a warm place rather than to lie them on the cold floor. The first castings of a day's run may be placed on a hot plate suitably heated, until such times as a sufficiently stable warm pile of castings has accumulated to receive the latest produced casting. The idea is to produce all the time what might be described as self-annealing conditions so that rapid temperature changes in cooling shall not cause cracking. If it is found, on subsequent machining operations that die-castings distort on removal of cast surfaces, then full scale annealing must be adopted as part of the manufacturing process.

REFERENCES

[1] D. R. Patent 530,440 (British Patent 348,470).
[2] British Patent 457,826.

CHAPTER 7

Pressure Die-Casting

THE PRESSURE DIE-CASTING of magnesium alloys can be carried out satisfactorily on machines of the cold chamber type which have been used satisfactorily on aluminium alloys for some years. Obviously the chemical reactivity of molten magnesium precludes its use in goose-neck type of machines owing to the appreciable oxidation which occurs in these conditions of casting. The apparent similarity of magnesium to aluminium in that they are both light metals and their alloys melt in a similar temperature range, should not lead the die designer and foundryman to use a similar technique. The different thermal properties of magnesium and its tendency to oxidation require a technique which takes these factors fully into account.

Die-Casting Machines

As indicated above the cold chamber machine is almost exclusively used in Great Britain and America and whilst this machine will be familiar to aluminium die-casters, a brief description of its principles of operation will be necessary, if only for the purpose of completeness. These are indicated in *Fig.* 24 from which it can be seen that the metal is transferred from the holding furnace to the injection cylinder by a hand ladle. As soon as this operation is complete an operating mechanism, such as a foot pedal or switch, is immediately brought into play forcing the metal into the die at high pressure. The speed of movement of the injection plunger and the pressure can be adjusted at will to meet the requirements of the individual components. Provision is made for the immediate return of the plunger after injection and the opening of the die at a suitable interval after casting.

Most of the machines of this type, particularly of American manufacture, have a horizontal injection plunger; a typical machine being shown in *Fig.* 25. There are, however, machines which use a vertical

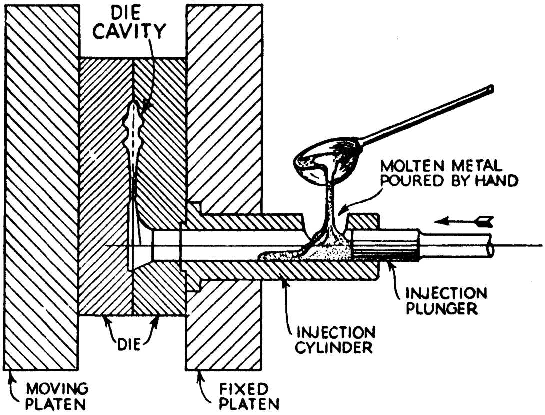


Fig. 24. Principle of cold chamber injection pressure die-casting machine. The molten metal is poured by hand into the injection chamber and the injection plunger is moved forward by hydraulic pressure.

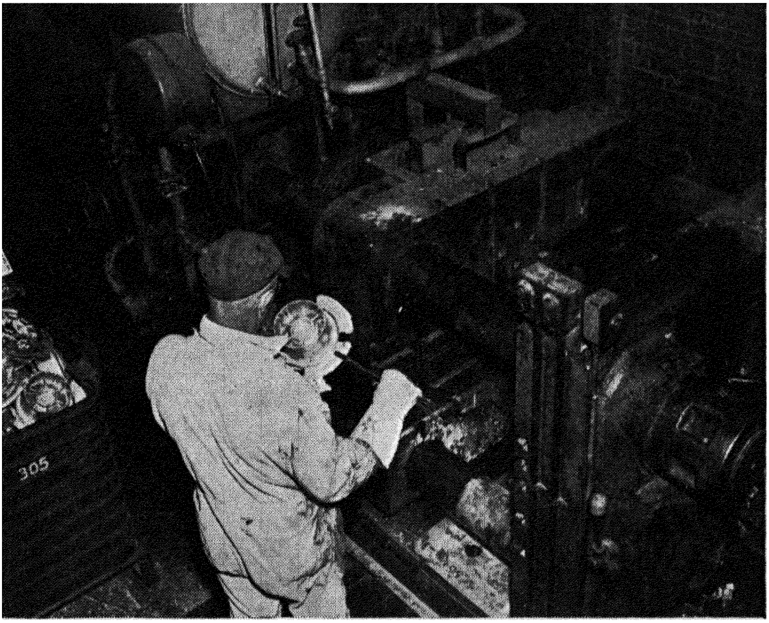


Fig. 25. Close-up of cold-chamber horizontal pressure die-casting machine of American design.

(*Dow Chemical Co.*)

injection plunger, so that the metal is forced out of the cylinder at right angles to the direction of travel. A very large machine of this type designed in Czechoslovakia over twenty years ago is also illus-

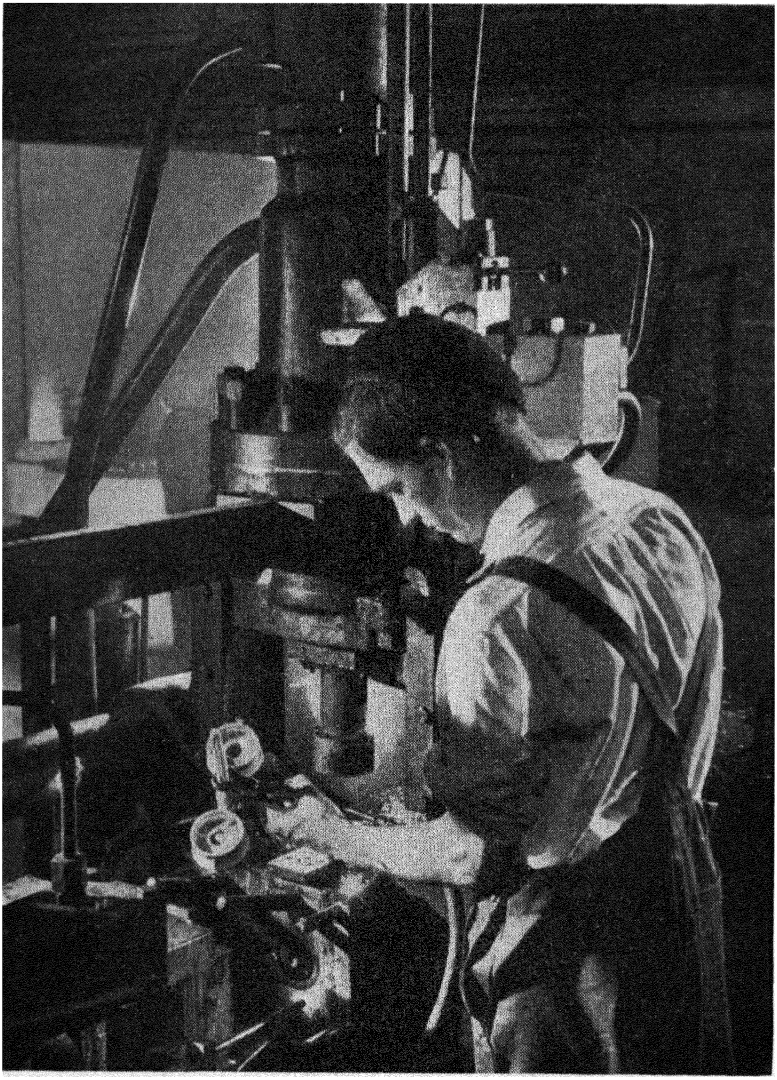


Fig. 26. Polak vertical plunger type cold-chamber machine.

(*High Duty Alloys Ltd.*)

trated. (*Fig*. 26.) This latter machine is claimed to have advantages over the more conventional designs, particularly on high speed of operation.

Whilst British and American practice has favoured cold chamber machines the hot chamber version has been successfully used in Germany for many years. Two basic types of machine are shown in *Figs*. 27 and 28. The first of these consists of an enclosed melting pot holding the liquid metal (*a*), and having a small opening (*b*) fitted

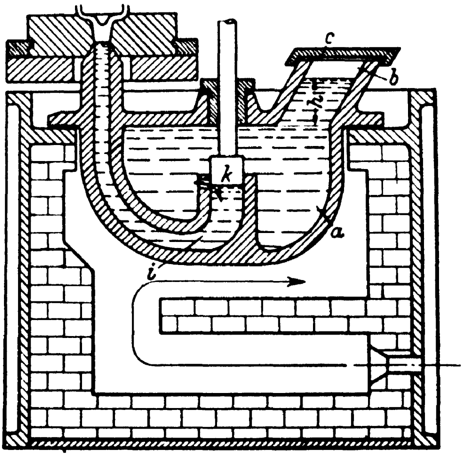


Fig. 27. Section of German hot-chamber die-casting machine—single chamber type.

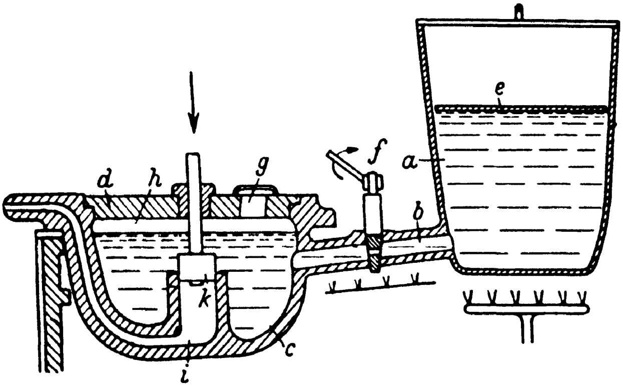


Fig. 28. German hot-chamber machine with separate melting chamber.

with a cover (*c*) through which ingot or molten metal is fed. The castings are produced by the movement of the piston (*k*) which on the downstroke forces metal in the pressure chamber (*i*) from whence it enters the die. Withdrawal of the plunger on the upstroke opens the port to the pressure chamber and permits a further quantity of molten metal to enter.

The second type (*Fig.* 28) is similar but the metal is melted in a separate chamber and connected by a heated tube with the injection chamber into which it flows usually by gravity. The flow is cut off once the injection chamber is full. This system makes for high output due to reduction of metal handling. Such machines are mainly hydraulically operated and the metal temperatures are around 650°C.–670°C. (1200°F.–1240°F.). It is considered however that the metallurgical standard of quality of German pressure die-castings is somewhat inferior to that of the general run of castings from cold chamber machines.

After some years of experiment the Dow Chemical Company have announced the development of a new hot chamber die-casting machine[8] which it is claimed overcomes the principal disadvantages of the previous types of hot chamber machines. The principle of its operation is relatively simple and is not dissimilar to goose-neck hot chamber machines used for zinc base die-casting but with modification to take into account the chemical and physical characteristics of magnesium.

It consists of two principal parts one of which is a supply pot or melting furnace which is used to provide a reservoir of molten metal and provide for the fluctuations between supply and demand during melting and casting. The published accounts indicate that it is usually of up to 500 lb. capacity, fully enclosed except for a hinged door through which either molten metal can be poured taken from a central melting unit, or solid metal added for melting.

The die-casting unit (*Fig.* 29) is supplied through a gravity flow or siphon pipe with molten metal which passes a control valve. This valve is actuated by an electrically controlled float which indicates the level of the metal in the chamber and opens the control valve when it falls below the required level. A hydraulically operated vertical piston forces metal through a closed injection gooseneck into the die in the same manner as the hot chamber goose-neck machine used for zinc die-casting.

At the time of writing there has been no experience with this machine in Great Britain. There appear to be a number of advantages to this type of machine and it may well put magnesium die-castings on a highly competitive basis with aluminium. In particular the rate of production possible should be higher than for the cold chamber machine and automatic cycle control introduced on really long runs.

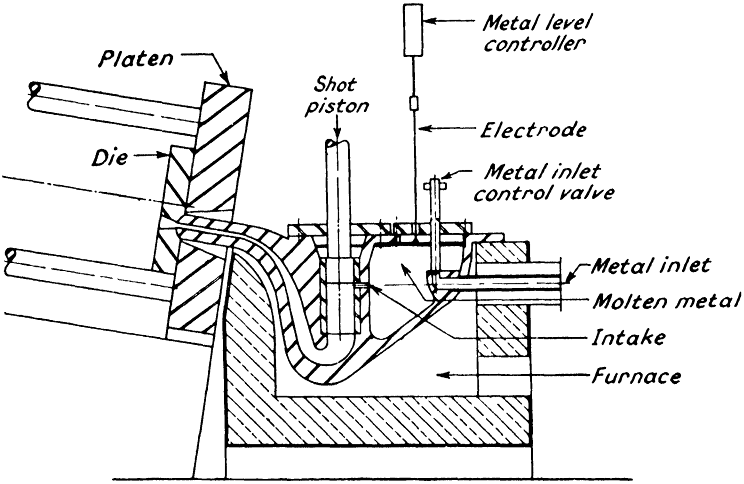


Fig. 29. Dow hot chamber die-casting machine showing principle features of construction.

Other advantages are that there is no chilling or variation in temperature of the metal due to transferring from the metal reservoir with a hand ladle, and the melting furnace can be charged without interference with the machine operator. The enclosed system also reduces oxidation and melting losses. The system also reduces the injection pressure required and increases die life as well as sometimes making possible smaller die blocks and core locks. Drippage in the sprue area has been eliminated and the nozzle is firmly inserted in the die.

The present design has only been found suitable for magnesium-aluminium alloys and for castings of no more than 2 lb. finished weight. Obviously if the apparent advantages of this machine are confirmed then not only will the field of application for magnesium die-castings be widened but attention will be given to designing larger machines and to developing techniques for pressure die-casting other alloys.

Having considered the types of die-casting machines available we must now make reference to the dies used in them, particularly the materials employed. Owing to the high operating temperatures alloy steels are essential, particularly those of the high chromium and tungsten type. No chemical attack of the die occurs due to alloying with the magnesium as is experienced when casting aluminium, but the high working temperature means that the steels must be resistant to heat checking.

Die Steels

The following Table 9 gives nominal compositions of die steels which have been found to give satisfactory service:

TABLE 9

Nominal Composition of Die Steels Suitable for Magnesium Die-Casting

	A	B	C	D	E	F
Carbon	0·40	0·40	0·35	0·40	0·35	0·35
Manganese	0·30	0·40	0·40	0·30	0·15	0·15
Silicon	1·00	1·00	1·00	1·00	0·20	0·20
Chromium	5·00	5·25	5·00	5·00	2·25	3·25
Molybdenum	1·00	1·00	1·50	—	—	0·30
Vanadium	0·50	1·00	0·30	—	—	0·30
Tungsten	—	—	1·25	5·00	3·50	8·00

It is necessary to ensure that these steels are correctly heat-treated. In the first place they should be annealed before commencing die-sinking operations, and on completion should be hardened and tempered to give a Brinell of around 400–450 which will provide a material with good resistance to heat checking and cleavage cracking with satisfactory wear resistance. For small pins and cores which are difficult to lubricate one of the high chromium stainless steels can be used, although for dies not required for long runs the rather cheaper lower chromium steels can be used such as A and B listed above.

The design of dies for pressure die-casting of magnesium alloys is an art mainly acquired from experience. However, the newcomer to this field can obtain some indication of the size and disposition of gates, injection pressures and speeds as well as casting temperatures, by comparing the physical properties of magnesium alloys with those of aluminium. It is understandable that the similarity in melting points between the two metals tends to lead the die-caster to use a similar technique, often with most unsatisfactory results. Further, with the development of alloys containing zinc, zirconium, cerium or thorium in various combinations, these alloys must be treated on their own merits in the same way as different techniques are necessary for the various types of aluminium alloys.

Magnesium Die-Casting Characteristics

The table below gives a number of physical characteristics of aluminium and magnesium at room temperature and in the liquid state which will help to make clear their differences.

TABLE 10

Some Physical Properties of Magnesium and Aluminium

	Magnesium	Aluminium[2]
Latent Heat of Fusion Cals/gm.	46·5[3]	92·4
Specific Heat (cals/gm/°C.)		
20°C.	0·25[4]	0·22
650°–750°C.	0·27[3]	
Thermal Conductivity (cals/cm^2/°C./cm/sec.)		
Pure Metal (20°C.)	0·35[4]	0·54
Casting Alloy (20°C.)	(*a*) 0·19[5]	(*b*) 0·37
Liquid Contraction %	3·97[4]	6·50
Specific Gravity (gm/°C.)		
20°C.	1·74[4]	2·70
700°C.	1·50	2·38

(*a*) L123 alloy (9·5 per cent Al, 0·5 per cent Zn) (*b*) LM6M alloy (12 per cent Si).

The heat content of 1 lb. of molten magnesium is

$$(650 \times {\cdot}25 + 46{\cdot}5) \times 453{\cdot}6 = 94{\cdot}8 \text{ K. Cals.}$$

i.e. (Rise in temp. × sp. heat + latent heat) × gm. per lb. = K. Cals per lb.

The heat content of 1 lb. of molten aluminium is

$$(650 \times {\cdot}22 + 92{\cdot}4) \times 453{\cdot}6 = 106{\cdot}8 \text{ K. Cals.}$$

Since magnesium is only two-thirds the weight of aluminium the heat content of unit volume will be decreased by that amount. The lower thermal conductivity of magnesium alloys will tend to increase the time interval before solidification due to lower rate of heat abstraction compared with aluminium. Assuming these factors are of equal significance the theoretical increase in injection speed for a magnesium alloy such as L123 (9·5 per cent Al, 0·5 per cent Zn) compared with an aluminium silicon die-casting alloy would be:

$$\frac{106{\cdot}8}{96{\cdot}8} \times \frac{1{\cdot}74}{2{\cdot}70} \times \frac{{\cdot}37}{{\cdot}19} = 1{\cdot}38 \text{ times greater.}$$

In fact injection speeds of 1¼ to 1½ times greater than for aluminium alloys are often used.

These values are only a guide and apply to magnesium alloys die-cast under the same conditions as an aluminium-silicon alloy. Now for practical and economic reasons one will endeavour to avoid using higher injection speeds and therefore pressures, than are essential. Most aluminium alloys are pressure die-cast using fairly thin gates, i.e. around 0·020–0·045 in. through the narrow section parallel with the die-face. If one considers the ejection of any fluid from an orifice under constant pressure it is obvious that an increase of the size of orifice will increase the rate at which it flows out. Hence increasing the thickness of section across the gate will reduce the maximum pressure needed for magnesium castings. Often a 'spray' gate with multiple inlets will be found the best solution with larger dies. Other alternative means can be used either independently of, or in conjunction with larger gates. Raising the casting temperature preferably by heating the plunger chamber, will facilitate casting; and to some extent a slightly warmer die will assist but the other measures are usually more reliable. Taking all of these factors into account there is no reason why good quality magnesium alloy die-casting should not be as readily produced as those now made in aluminium alloys. In fact, as will be more fully discussed in the last chapter, owing to there being no tendency for magnesium to alloy with the die, improved accuracy on cored and blind holes and even across the width of the casting can be obtained compared with aluminium alloys.

The machines used for pressure die-casting normally produce injection pressures of 5,000–20,000 lb./sq. in. and locking pressures of 100–600 tons. The choice of machine used on any individual die will depend upon the size and complexity of the component, higher pressures being needed as these factors increase. Apart from choosing a machine of adequate capacity it is desirable to determine the machine settings and conditions of operation by pre-production trials.

Casting Conditions

In the foregoing paragraphs we have discussed the factors influencing the injection speeds and pressure necessary. However, it is equally important that these values should be based on operation at an optimum casting temperature which will be in the range 635°–680°C. (1180°–1220°F). This maximum temperature should not be exceeded because of the dangers of oxidation at higher temperatures.

The die temperature will also have to be established and is normally in the range 200°–250°C. (390°–475°F.). With a high rate of output it is not unusual to find that the die tends to overheat if no cooling is applied, and this often shows itself as hot cracks in the castings or distortion during ejection. Many dies will require the provision of channels for water cooling, and these should be placed near the heavier section. A lubricant is normally applied to the die surface and these are usually proprietary organic compounds of which the 'Oil Dag' type containing colloidal graphite is an example. A non-proprietary material referred to in one account[6] which gives good results on many jobs is cocoa butter. It is by no means necessary to apply lubricant between each injection, an application every three to five casts is often sufficient. There is often a tendency to apply lubricant too generously with a resultant loss of surface quality.

In addition to using the correct casting conditions it is also necessary to ensure that the casting is ejected from the die after allowing the correct interval between injection and the opening of the die. If there are several separate withdrawable cores the correct sequence of removal should be established and adhered to. Too early removal from the die will result in distortion of the casting and the opposite

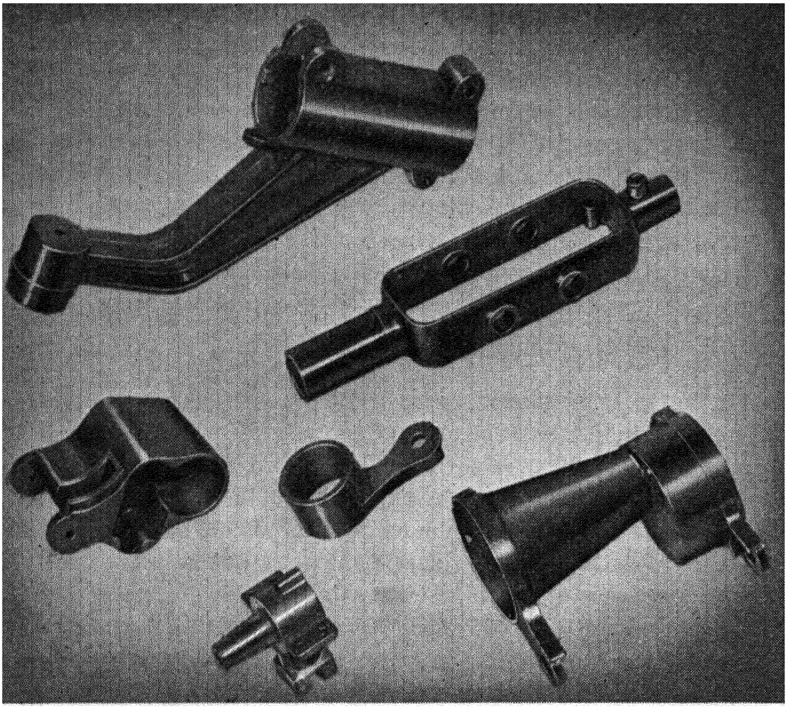


Fig. 30. A group of magnesium alloy pressure die-castings.
(*Stone-Fry Magnesium Ltd.*)

condition will often lead to hot cracking. The dwell period will be found to vary from a few seconds for small castings to about 30 sec. for the largest castings normally in production at present.

It will usually be found that the output magnesium die-castings per hour will be about 15 per cent to 30 per cent greater than for a similar job in aluminium. However there is a tendency for the amount of scrap to be higher with magnesium, particularly in foundries producing die-castings in the metal with little experience. One of the principal defects is a certain roughness of surface due to oxidation at hot spots in the die. This can often be overcome by adjustments to the cooling arrangements. Another common defect which may be important where painted or other finishes are to be subsequently applied, is existence of flow lines, sometimes accompanied by oxidation. The remedy to this trouble lies in adjustments to the gating systems to produce a smoother entry of the metal and where relatively small patches are found the judicious placing of small overflow wells into which the defective metal can be channelled and subsequently trimmed off, may provide a complete remedy.

On the other hand the freedom from sticking in the die can mean that castings are possible in magnesium which would not be possible in aluminium. An example quoted in a published account[7] refers to an angle block used in a printer's chase. The part was 5 in. sq. and contained thirteen cores, $\frac{3}{8}$ in. diameter, in each half of the die so as to give a honeycomb structure. The total taper on the cores was 0·001 in. and the tolerance ± 0·001 in. A control dimension of $2\frac{1}{2}$ in. between two points was held to ± 0·002 in. on the nominal dimension. Generally speaking the taper on cores $\frac{3}{8}$ in.–$\frac{3}{4}$ in. long will be about 0·3 per cent–0·6 per cent of the depth of hole as compared with 0·6 per cent–1·0 per cent for aluminium. Similarly, the maximum hole depth possible will be higher and the minimum hole depth lower than for aluminium alloys, and the dimensional accuracy will similarly be greater.

It can be seen therefore that magnesium can be satisfactorily die-cast and certain of its properties make possible improved tolerances compared with those currently obtained with aluminium. Recent developments in alloy technology suggest that improved materials for pressure die-casting are likely to be found once the casting properties of these materials have been assessed. Such trends together, it is hoped, with a fuller exchange of information on pressure die-casting techniques should provide the basis for a substantial increase in the use of magnesium die-castings which can be well justified on their technical merits.

REFERENCES

[1] German Patent 521,601. (British Patent 289,693.)

[2] VON ZEERLEDER. *Technology of Light Metals.* Elsevier and Co. Inc. (1949), p. 45.

[3] J. H. AWBERG and E. GRIFFITHS. *Proc. Phys. Soc.* (London) (1925–6), **78**, 295.

[4] A. BECK. *Technology of Magnesium and its Alloys.* F. A. Hughes and Co. Ltd. (1941), p. 101.

[5] A. BECK. *loc cit.*, p. 113 (unpublished work due to K. E. Mann).

[6] G. C. CLOSE. Magnesium Die-Casting. *Machinery* (London) (1952), **81**, 2076, 387–9.

[7] G. F. HODGSON. Magnesium Die-Casting. *Foundry* (1954), **82**, 2,102–5, 252–4.

[8] U.S. Patent 2,660,769, see also ANON. *Precision Metal Moulding* (1955), **13**, (1), 37, 38, 48.

CHAPTER 8

The Heat Treatment of Magnesium Alloy Castings

THERMAL TREATMENTS are applied to magnesium castings for the same reasons as they are given to castings in other metals, namely to improve mechanical properties or to remove residual stresses in components produced by restraint on the metal during solidification. Before considering heat treatment practice it is helpful to summarize the essential theory upon which it is based.

Heat Treatment Theory

The magnesium alloys containing aluminium as their principal alloying element may be referred to as an example of the application of metallurgical theory to practical heat treatment. In the as-cast condition the 10 per cent aluminium alloy (L123) will show a two-phase structure under the microscope. This means that when highly polished and lightly etched the material examined under a high magnification will show two differently coloured portions as is illustrated in *Fig.* 31. The darker outlined portions are due to a constituent known as a eutectic which is formed from a compound of magnesium and aluminium (referred to as an intermetallic compound) and the magnesium solid solution which contains some dissolved aluminium.

In considering magnesium alloys (Chapter 2) it was indicated that more aluminium will dissolve in the magnesium at high temperatures than at room temperature. Therefore if a magnesium alloy casting is heated to a temperature between 400°C. and 430°C. the second phase containing the excess aluminium will dissolve and give a single phase solid solution structure as shown in *Fig.* 32. The operation is known as solution heat treatment. The effect of this treatment is to improve mechanical properties such that the tensile strength and elongation is appreciably increased whilst the 0·1 per cent proof stress and hardness are little affected.

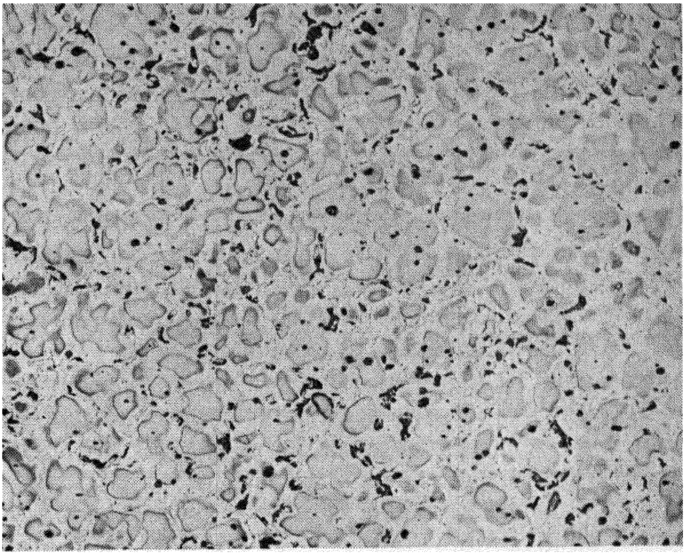


Fig. 31. Microstructure of Mg-10 per cent Al Alloy as cast—etched 2 per cent nital (× 150). (*Magnesium Elektron Ltd.*)

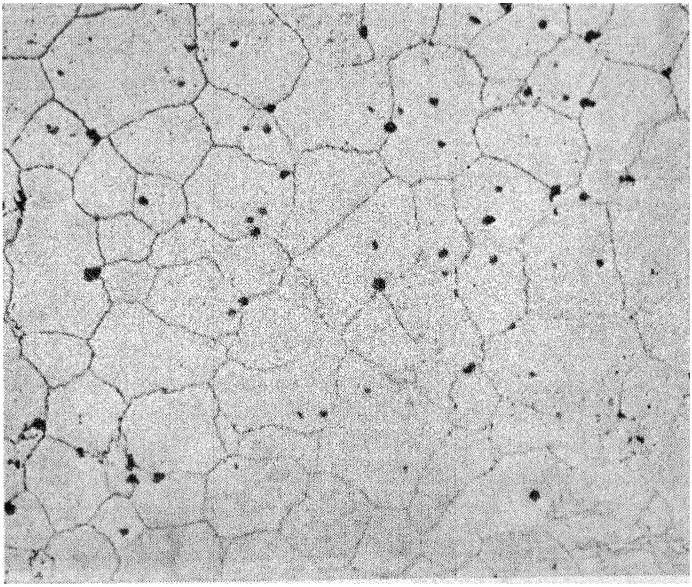


Fig. 32. Microstructure of Mg-10 per cent Al Alloy after solution heat treatment—etched acetic—picral (× 150). (*Magnesium Elektron Ltd.*)

The time of heat treatment of magnesium alloys must be sufficiently long to ensure virtually complete solution of the aluminium constituent, and the temperature must not exceed 437°C. (820°F.) at which point the eutectic melts. In practice, some traces of eutectic usually remain undissolved.

The solution treated alloy is stable and there is no tendency for it to further harden when left at room temperature (age harden) as occurs with the aluminium alloy usually known as Duralumin, which progressively increases in strength after solution heat treatment reaching its maximum in about five days at room temperature.

There is a further heat treatment which can be applied to the material following solution treatment, and that is precipitation hardening or artificial ageing as it is sometimes called. This involves reheating the castings to a temperature in the range 160°C.–220°C. (320°F.–425°F.) for a suitable period. This results in the reappearance of the eutectic in a finely divided ('precipitated') form (*Fig.* 33). The castings so treated are usually described as 'fully heat-treated' or 'solution

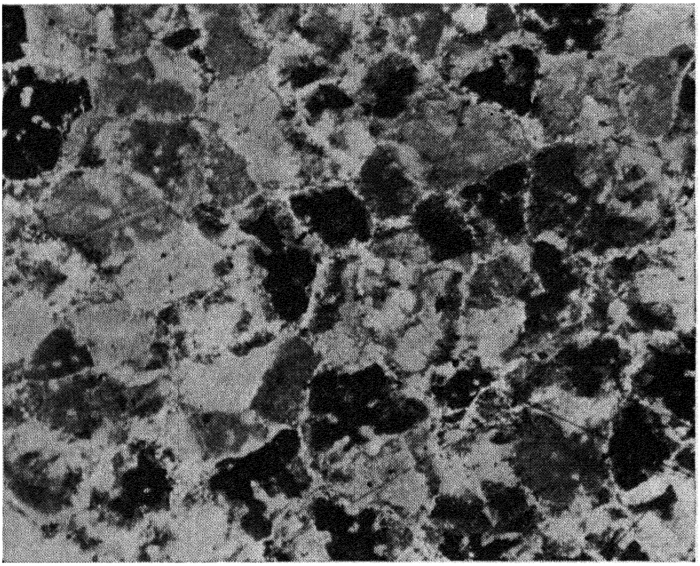


Fig. 33. Microstructure of Mg-10 per cent A1 Alloy fully heat treated—etched 1 per cent nital. (× 150).

(*Magnesium Elektron Ltd.*)

heat-treated and aged'. Table 11 indicates the change in properties obtained by heat treatment on typical test bars in this alloy.

TABLE 11

Effect of Heat Treatment on Mechanical Properties of L123(AZ91)

Condition	0·1% P.S. Tons/sq. in.	U.T.S. Tons/sq. in.	Elong. %	Brinell Hardness
As-cast	4·8	9·1	1·5	58
Solution treated	5·0	15·8	7·5	60
Fully heat-treated	7·8	15·4	1·2	78

It can be seen that artificial ageing increases the 0·1 per cent proof stress and hardness, decreases the elongation and has little effect on ultimate tensile strength. Detailed study of the effect of various combinations of ageing temperature and treatment time is contained in various papers dealing with AZ63A, AZ91 and AZ92A alloys, and binary magnesium-aluminium alloys.[1,2,3]

A further thermal treatment, often referred to as 'annealing' but more correctly called 'stress-relieving' or 'stabilizing', is used to ensure freedom from internal stresses which may be produced during casting. It is only normally applied to castings which are not given any other heat treatment and in American terminology corresponds to the T5 condition. In this treatment a relatively low temperature is used which is without any major effect on the mechanical properties, giving for aluminium containing alloys a slight increase in tensile strength and decrease in elongation.

Such stress-relief heat treatments have become particularly important in connexion with the production of gas turbine components where dimensionally stable castings are vital. The production of such items is by no means a simple problem with intricate parts and is complicated by the fact that with creep resistant alloys such as those containing cerium, treatment at temperatures sufficient to produce complete freedom from internal stress may adversely affect creep properties. This subject has been examined and discussed at some length in a paper by Payne[4] in which he reports the results of careful tests made to assess the degree of freedom from stress-relief given to castings in L121 (AM80A), L123 (AZ91A), DTD 721A (ZK51A) and DTD 728 (EK41A).

Details of recommended heat treatments for the various alloys are discussed in detail later, but as might be expected industrial practice is often a compromise between conditions that are theoretically desirable and what can be economically achieved in production. Apart from determining the thermal treatment appropriate to any alloy it is necessary before discussing these to consider the types of furnace and atmosphere appropriate to magnesium heat treatment. It has already been emphasized that prevention of oxidation is one of the fundamentals of magnesium technology, and the provision of a medium which ensures this condition is a prerequisite to successful operation.

Salt Baths

The simplest method of heating magnesium alloy castings for solution treatment is by the use of a fused chromate salt bath which prevents oxidation and produces a grey-black film on the surface. This equipment is similar in design to that used for solution heat treatment of aluminium, but the salt mixture used consists basically of 3 parts of sodium dichromate, 1 part of potassium dichromate melting at 350°C. to which 1–3 per cent of sodium chromate is added to reduce the tendency for sludge formation.[5]

The first melting down of the salt mixture must be carried out carefully and only a little added at a time since there is sometimes chemically combined water present and this must be 'boiled off' before any castings are introduced. This also means that introduction of small quantities are desirable since not only does it facilitate removal but eliminates the possibility of the salt being spattered by the reaction of the moisture in unfused salt with the molten material. It must be strongly emphasized that the salts used for heat treatment of aluminium must on no account be used for magnesium alloys since a reaction of explosive violence will result.

The salt bath may be heated by gas, oil, electricity or solid fuel; and the arrangement of burners and disposition of flues must ensure evenness of temperature distribution so that the variation at any point does not exceed ± 3°C.(5°F.) of the mean temperature. The furnace should be fitted with a hinged lid which can be kept closed except during loading and unloading. Pyrometric control is essential and there should preferably be two thermo-couples in the bath which should be at least 3 in. from the side of the bath to avoid false readings due to the walls being somewhat hotter than the salt.

The chromate salt bath has the advantage of a relatively low initial capital outlay and very efficient heat transfer. However, there are drag-out losses of the salt retained of the castings and racks which have to be made good. As a guide it can be indicated that about 1½ to 2 cwt. of salt will be required for each ton of castings treated. Occasional removal of sludge, about three- to six-monthly intervals will be necessary, using a perforated flat-bottomed scoop. Replenishment of salt will be needed every few weeks to make up for drag-out losses.

It should be noted that magnesium alloy castings are of lower specific gravity than the molten salt and they float therefore. To overcome this difficulty castings to be treated are loaded into a perforated metal basket, the castings being secured by iron wire in the simplest cases.

It is often found, however, that other means of sinking have to be adopted, especially when treating thin sectioned castings which must be completely free from distortion. In such cases, it is necessary to make use of jigs designed to support those sections of a casting which might warp on accidental stressing during the period of immersion in the salt. Iron jigs may be used on the grounds of cheapness, but, since they will materially increase the weight of the charge to be loaded, it is preferable to use aluminium jigs. The specific gravity of aluminium jigs is sufficiently high to effect sinking. They should not be used when treating zirconium containing alloys. The salt bath method is simple, thermally efficient, and comparatively inexpensive in equipment costs. Practical disadvantages are that the castings, when removed from the bath, are covered with a film of solidified chromate salts which has to be removed by washing in warm water. Not only are there drag-out losses of salt, but there is the danger to operatives of the incidence of dermatitis associated with chromates.

On this account operatives should be carefully instructed on its correct operation. Above all they should not inhale over the open bath or load or unload work without being protected by rubber gloves, aprons and thigh boots. Care should be taken when handling castings with chromate salts adhering that they are not conveyed accidentally to the nose. Where for maintenance or other purposes it is necessary for operatives to be exposed to the fumes from the bath they should be provided with protective glasses and inhalers.

It is also important that a lanolin-base hand-cream is applied before commencing work and that personal cleanliness, particularly washing of face and hands before meals, is scrupulously observed. No operative having any cut or wound should be allowed to work with chromate salts. The incidence of chrome dermatitis is much less amongst dark persons than fair, and this should be taken into account in selecting personnel. If the above precautions are observed there should be no danger of trouble from this disease.

Protective Atmospheres

Owing to the necessity of hand-cleaning the castings after treatment in the salt bath, and limitations on the size of components which could be conveniently handled, treatment in normal furnace atmospheres to which was added or in which was maintained, a definite sulphur dioxide concentration became an established practice which now predominates in magnesium heat treatment. This addition was first simply effected by the addition of sulphur and iron pyrites to the furnace. Suitable quantities of these materials were placed on shallow trays which were distributed amongst the work load. Under the influence of the temperature at which magnesium alloys are heat treated, sulphur burns to the dioxide, while pyrites oxidize to an iron oxide with the evolution of sulphur dioxide gas. In the absence of data on the subject of actual concentration of sulphur dioxide necessary to restrain oxidation, one could only guess at quantities of sulphur and pyrites to be used, and trust to luck that something was left at the end of a long treatment period. It was necessary to make ovens reasonably gas-tight, although it must be admitted that the characteristic smell of the gas issuing from a less than perfect gas-tight oven was a useful practical indication that the protective gas continued to be evolved.

Obviously, in such cases, the atmosphere could not strictly be said to be 'controlled', that is, not quantitatively controlled, except in the sense that an unknown minimum concentration was more or less accidentally produced. Further, it is known that presence of sulphur dioxide is deleterious to the resistance wire elements of an electric furnace and on the element wires of thermo-couples. It is therefore desirable that gas concentration should not be greater than that required for protection.

Whilst the use of sulphur dioxide prevents oxidation there are certain drawbacks associated with its use, and acceptance of it as an essential constituent of the furnace atmosphere should not be dogmatic. It is possible to enunciate a practical rule, subsequently to find that its unreasoning acceptance actually hinders development, because by acceptance, further thought is indeed actually discouraged. An example from the authors' experience will show how a truly paradoxical situation can develop within one organization. Magnesium alloy billets for forgings were produced in the ingot shop. As is well known, such material is normally solution treated before despatch to the forge: this thermal treatment was therefore given in a fused chromate salt bath or in a controlled atmosphere electric furnace. Preparatory to the first forging operations, the billets were again 'soaked' for a period of twelve hours at a temperature of about 400°C. (752°F.). This soaking treatment was given in the forge shop, and in this case, the need for a special atmosphere was forgotten, and yet no noticeable oxidation occurred. It is true that the forge shop ovens were gas-fired and products of combustion circulating in the oven may have had an inhibiting effect. The point is, however, that the need for special requirements was not consciously considered, and that either suitable working conditions were accidentally achieved, as will be shown was probably the case, or that in fact atmosphere control was not as critical as theoretical considerations based on incomplete knowledge would appear to suggest.

There has been more careful work carried out under practical conditions which help to elucidate the mechanism of the protection offered by sulphur dioxide to magnesium castings during heat treatment. It is not easy to ensure a gas-tight heat-treatment furnace for production purposes. Observations of a pit-type electric resistance furnace which had been made as gas-tight as possible showed that whilst sulphur dioxide leaked to the atmosphere during the first hours of treatment there was little in evidence towards the end of the treatment and only small quantities could be detected chemically.

Castings from the furnace were not badly oxidized but, in fact, a protective film appeared to have formed on the surface. Subsequent experience has shown that provided about 1 per cent of sulphur dioxide is present in the furnace atmosphere in the early stages of treatment the quantity present subsequently is less critical. The quantity of iron pyrites to produce a satisfactory protective atmosphere has largely been arrived at empirically. A French handbook[6] recommends 5–10 kg. of pyrites for every cubic metre of capacity, or 2·5 kg. for every 100 kilos of work loaded; these figures being based on a load of 500 kilos. In British units this would be 2¾ lb. of pyrites to every hundredweight (112 lb.) of castings, based on a 10 cwt. load or alternatively 11–22 lb. of pyrites for every 10 cu. ft. of furnace volume.

The recommendations of the American Foundrymen's Association on heat treatment of magnesium castings[7] are also of interest. It is stated that solution treatment of the alloy corresponding to AZ63A (6 per cent Al 3 per cent Zn) can be carried out either in gas-fired or electrically heated furnaces, but the treatment of AZ92A (9 per cent Al 2 per cent Zn) should always be done in an electrically heated, gas-tight furnace; thus suggesting that continuous protection is necessary. The atmosphere recommended for AZ92A is one containing 0·7–1·0 per cent sulphur dioxide, and it should not be allowed to fall below the maximum figure as then a dangerous condition would arise and a fire would result. On the other hand, 0·3 per cent sulphur dioxide is stated to be adequate for AZ63 when heated in an electric furnace.

It would appear that these recommendations may be modified to some extent in the light of the experience described above, and this constitutes an example of the divergence of opinion which exists on aspects of magnesium technology. It certainly is not clear why protection at the higher rate of sulphur dioxide concentration is insisted upon for AZ92A as it contains a larger proportion of alloying elements than AZ63A. In addition, it is certain that the rate of oxidation decreases with increasing alloying content—at least this is true of alloys in the molten condition—yet these American recommended practices imply that the alloy with greater alloying proportions is the more readily oxidized, probably due to the tendency of the β phase to oxidize preferentially.

It will be realized now that there are many alternative methods of heat treating magnesium alloys. The fused chromate salt bath was perhaps the earliest method, and while it has the advantage that the work pieces are mechanically supported by the molten salt, it suffers from the complication of all industrial processes utilizing chromate—that of the ever present possibility of the incidence of chrome dermatitis.

The gas-tight, or near gas-tight, oven into which sulphur dioxide is fed, or produced *in situ*, is a further practical method, but sulphur dioxide is an acquired taste to which foundry personnel do not take with enthusiasm. It may be pointed out that it is known that a small concentration of carbon dioxide will restrain oxidation during heat treatment. It is believed that the appropriate carbon dioxide content must be maintained throughout the treatment period, as distinct from sulphur dioxide which it appears, need be used for the first six or seven hours only; other work on the inhibition of oxidation of molten magnesium alloy has indicated that carbon dioxide is much less effective than sulphur dioxide, and it is now, therefore, cautiously argued that the difference in result postulates the maintenance of a continuous carbon dioxide concentration at some level. There seems to be little published information regarding this use of carbon dioxide.

A further alternative means of producing a suitable atmosphere has been proposed and used. In the recognition that oxygen and water are oxidizing agents and especially at high temperatures, atmospheres for heat treatment of the metal have been given by the products of incomplete combustion of town gas, such that no oxygen is present, and from which all moisture has been removed. The production of this atmosphere necessitates the installation of a town gas-burning equipment; the resultant gas mixture fed into the furnace has an approximate analysis of 20 per cent carbon monoxide, 80 per cent carbon dioxide, nil oxygen, and nil moisture. Careful analytical check on the maintenance of the composition of this atmosphere is vitally necessary, for the presence of even 1 per cent oxygen, in these conditions, results in violent oxidation to an extent sufficient to scrap the load. In the United States cracked city gas, which may contain hydrogen, methane, carbon monoxide and some nitrogen, is also satisfactory.

In view of this, it is perhaps surprising that a successful method of magnesium alloy heat treatment proposed in 1941[8] makes use of an atmosphere containing water vapour and oxygen. Such an atmosphere may be produced by any simple means—either by blowing steam into the oven, or by allowing the products of combustion of carbonaceous fuel to mix with the air in the furnace air circulating system. It appears that a protective oxide film is produced; it is probable that the mechanism of film formation under the conditions described is not fully understood, for from theoretical considerations magnesium oxide is not normally protective. That a film of unique properties is produced, however, is confirmed by the fact that magnesium alloy articles so treated are fairly resistant to corrosion. Although publication of this patent was subject to some scepticism in

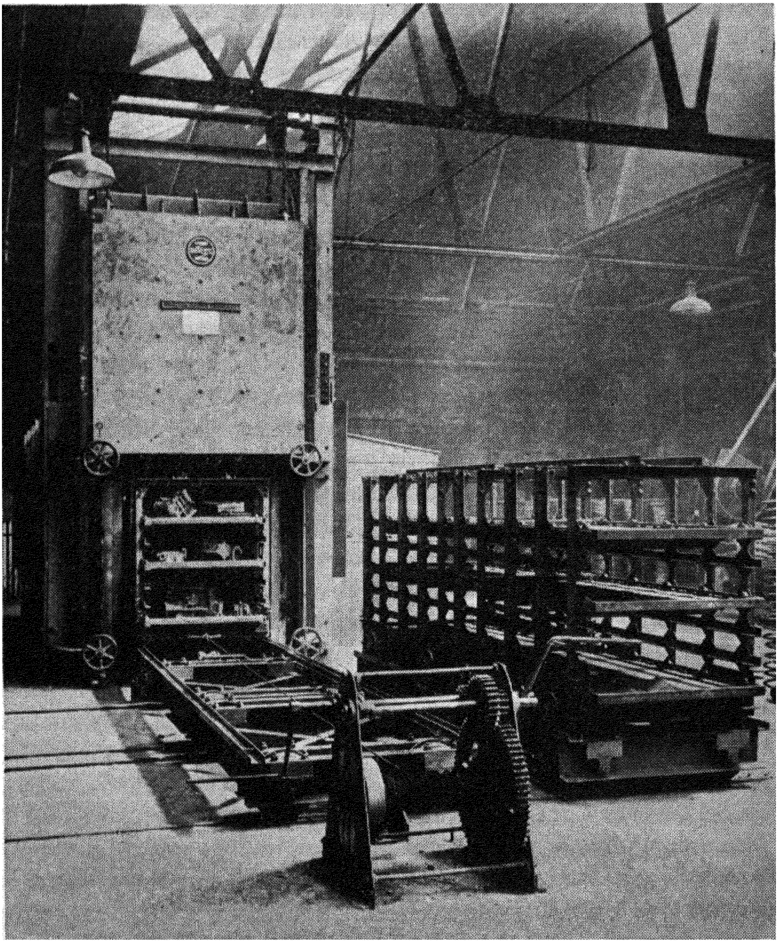


Fig. 34. Electrically heated furnace used for heat treatment of magnesium castings.

(*Birlec Ltd.*)

certain quarters the method has worked satisfactorily in production for a number of years.

The simplest method yet proposed also makes use of protective film formation. An American practice[9] consists in the immersion of the castings in a 10 per cent aqueous solution of hydrofluoric acid until action ceases. This treatment produces a surface film of protective fluoride, and then castings so treated may be heated in any suitable oven without regard to chemical composition of the atmosphere. This method has been experimentally tested in Great Britain and given satisfactory results.

This discussion of protective atmospheres for the heat treatment of magnesium castings is mainly applicable to solution treatment conditions only. When precipitation treatment is carried out precautions against oxidation are largely unnecessary since the protective film formed during solution treatment remains effective and at precipitation temperatures (175°C.–210°C.) oxidation is relatively slight. Having established the conditions necessary for satisfactory heat treatment it is appropriate to consider some of the practical points relating to heat treatment of castings in various alloys.

Heat Treatment Practice

Before the castings are loaded into the furnace care should be taken to ensure that they are free from dust, particularly fine magnesium powder produced by grinding in the dressing operations, else there is a possibility of an explosion subsequently occurring in the furnace. The castings should be placed on suitable racks having a flat base; generally speaking castings should not be loaded on each other although this may be permissible where small light castings can be placed on larger heavy sectioned castings without risk of distortion. Similarly there should be a gap between each casting both to facilitate free circulation of the heating medium and to avoid the possibility of distortion due to expansion. Where necessary suitable steel jigs may be employed to support large overhanging sections where distortion occurs if left unsupported.

Tests made by the authors on the distortion produced during the solution heat treatment on L124 (AZ91A) 1 centimetre square bars supported at one end only are of interest in this connexion. It was established that the amount of distortion, measured as the amount of sagging of the unsupported end of the bar after solution heat treatment, varied directly with the temperature. In other words the higher the solution treatment temperature the more liable the castings were to sagging. Further the amount of sagging varied with the square of the distance from the supported end thus showing it to be dependent upon the mass or thickness of material unsupported. Castings should therefore be given as much support as is practicable, particularly where a large weight of castings is supported on a relatively thin flat base.

As is often the case in production some compromise has to be arrived at since the nearer the solution treatment temperature is to the eutectic point the more complete is the homogenization of the material. On the other hand higher temperatures bring more danger of eutectic fusion from accidental local hot spots in the furnace or segregation in the casting. The temperature chosen will be usually about 20°–30° below the eutectic point.

Difficulties have been experienced with eutectic fusion when solution heat treatment is carried out at normal temperatures due to local segregation of the constituents producing a eutectic of abnormal composition which may have a low melting point. This can be overcome by stepping up the heat treatment temperature in stages. With the alloy L124 (AZ91A–T4) a heat treatment cycle of raising the casting to 390°C. (735°F.) and holding at that temperature for five to eight hours, followed by twelve hours at 400°C. (750°F.) and ten hours at 410°C. (770°F.) has been proposed[10] and applied industrially as a means of obviating any difficulties due to fusion of local low melting segregation.

This treatment will not only avoid any overheating troubles but will reduce any risk of abnormal grain growth[11] which may occur in casting alloys when internal stresses are present prior to heat treatment. Some foundries have operated quite successfully a simple heat treatment in which a constant temperature is maintained after raising the temperature of the furnace and work-load from room temperature. Alternatively the castings can be placed into the warm furnace, providing the temperature does not exceed 250°C., and then raised to the solution treatment temperature.

Whilst difficulties such as eutectic fusion or abnormal grain growth are by no means common production problems it is necessary for any foundry to know how to overcome them. Although the above measures will be helpful it is usually desirable to tackle them

TABLE 12

Heat Treatment of British Magnesium Casting Alloys

Specification (or Designation)	Nominal Composition	HEAT TREATMENT OPERATION		
		Solution	Precipitation	Stress-relieving
L121	8% Al, 0·5% Zn	—	—	2 hours at 330°C.
L122	8% Al, 0·5% Zn	24 hours at 410°C.	—	—
L123	10% Al, 0·5% Zn	—	—	2 hours at 330°C.
L124	10% Al, 0·5% Zn	{ 6 hours at 385°C.	—	—
L125	10% Al, 0·5% Zn	12 hours at 400°C.		
		10 hours at 410°C.	12 hours at 185°C.	—
DTD. 684	8% Al, 0·5% Zn } High Purity	—	—	2 hours at 330°C.
DTD. 690	8% Al, 0·5% Zn } High Purity	24 hours at 410°C.	—	—
DTD. 708	3% rare earths, 2·3% Zn, 0·6% Zr	—	12 hours at 180°C.	(12 hours at 230°C.)*
DTD. 718	3% rare earths, 0·5% Zn, 0·6% Zr	—	12 hours at 180°C.	(12 hours at 230°C.)*
DTD. 721A	4·5% Zn, 0·7% Zr	3 hours at 330°C.	—	—
DTD. 728	3% rare earths, 0·6% Zr	—	12 hours at 180°C.	(12 hours at 230°C.)*
DTD. 748	4·0% Zn, 1·2% rare earths, 0·6% Zr	3 hours at 350°C.	—	—
ZT1	3%Th, 2·5%Zn, 0·7%Zr	16 hours at 315°C.	—	—
TZ6	5·8%Zn, 1·8%Th, 0·7% Zr	2 hours at 350°C.	—	—

* This is only used when the stress relief afforded by normal ageing treatment is inadequate.

TABLE 13

Heat Treatment of American Magnesium Casting Alloys (ASTM.B80–55T)

Alloy Designation and Temper		Nominal Composition	HEAT TREATMENT OPERATION		
			Solution	Precipitation	Stabilizing
AM80A	—F	8% Al, 0·2% Zn	—	—	—
	—T4	8% Al, 0·2% Zn	Raise to 775°F. (410°C.) in 2 hours. Soak 18 hours (min.) at 775°F.	—	—
	—T6	8% Al, 0·2% Zn	Raise to 775°F. (410°C.) in 2 hours. Soak 18 hours (min.) at 775°F.	16 hours at 350°F. (175°C.)	—
AM100A	—T6	10% Al, 0·2% Zn	Raise to 775°F. (410°C.) in 2 hours. Soak 18 hours (min.) at 775°F.	16 hours at 350°F. (175°C.)	—
AZ63A	—F	6% Al, 3% Zn	—	—	—
	—T5	6% Al, 3% Zn	—	—	2–5 hours at 450°–550°F. (232°–287°C.)
	—T4	6% Al, 3% Zn	Raise to 730°F. (387°C.) in 2 hours. Soak 10 hours (min.) at 730°F.	—	—
	—T6	6% Al, 3% Zn	,, ,,	6–18 hours at 350°–425°F. (175°–220°C.)	—
AZ91C	—F	9% Al, 0·7% Zn	—	—	—
	—T4	9% Al, 0·7% Zn	Raise to 770° F. (410°C.) in 2 hours. Soak 18 hours (min.) at 770°F.	—	—
	—T6	9% Al, 0·7% Zn	,, ,,	6–18 hours at 350°–425°F. (175°–220°C.)	—

AZ92A	—T5	9% Al, 2% Zn	—	—	5 hours at 425°F. (220°C.)
	—T4		Raise to 770°F. (410°C.) in 2 hours. Soak 18 hours (min.) at 770°F.	—	—
	—T6		,, ,,	6–18 hours at 350°–425°F. (175°–220°C.)	—
EK30A	—T6	3% rare earths, 0·7% Zr	18 hours at 1050°F. (565°C.)	16 hours at 400°F. (205°C.)	—
EK41A	—T5	4% rare earths, 0·7% Zr	—	—	12 hours 350°F. (175°C.)
	—T6	4% rare earths, 0·7% Zr	18 hours at 1050°F. (565°C.)	16 hours at 400°F. (205°C.)	—
EK33A	—T5	3% rare earths, 3% Zn, 0·7% Zr	—	—	12 hours at 350°F. (175°C.)
ZK51A	—T5	5% Zn, 0·7% Zr	—	—	2 hours at 625°F. (330°C.)
ZK61A	—T6	6% Zn, 0·7% Zr	1–5 hours at 900°F. (480°C.)	24–36 hours at 265°–300°F. (130°–150°C.)	—
HK31A	—T6	3% Th, 0·7% Zr	2 hours at 1050°F. (565°C.)	16 hours at 400°F. (205°C.)	—
ZH62A	—T5	5·8% Zn, 1·8% Th, 0·7% Zr	—	—	24 hours at 300°F. (150°C.)

at their source by modifying the casting technique to reduce the cooling time on heavy sections where segregation can occur and adjusting the core mix to give adequate collapsibility for sand cores or die temperature or removal sequence on die castings.

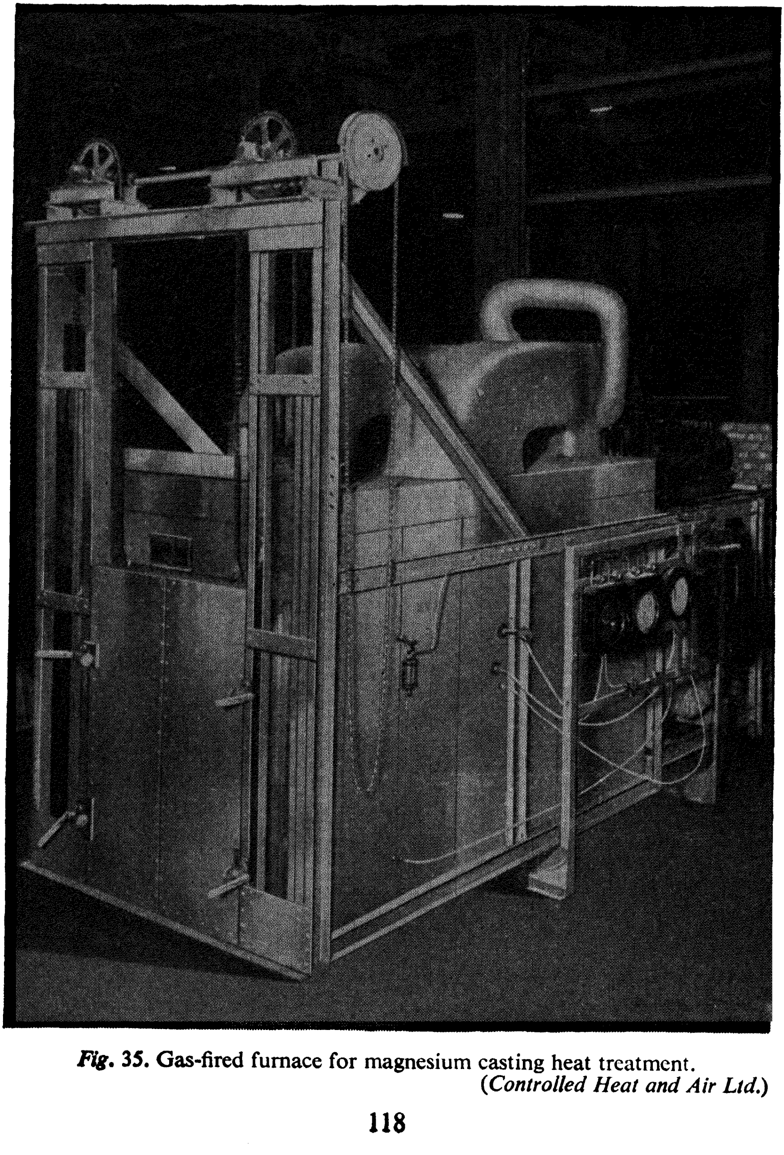


***Fig.* 35.** Gas-fired furnace for magnesium casting heat treatment.
(*Controlled Heat and Air Ltd.*)

When castings are removed from the furnace after solution treatment it is common practice to allow them to air cool, often with the assistance of an air blast. Some American work[2] on the effect of hot water quenching on the mechanical properties of AZ92, AZ91 and AZ63 alloys indicated that there was some improvement in strength and ductility (10 per cent or more) if the castings were quenched in water at 180°F. (82°C.) after solution heat treatment which was followed by ageing. This practice has not been adopted in Great Britain, where most castings are only solution heat treated; and it is believed that it has only had limited use in the United States.

Tables 12 and 13 give the heat treatment cycles appropriate to the common British and American alloys. Those containing aluminium and zinc as the major alloying elements enjoy a certain flexibility as to solution and ageing conditions and the recommendations are intended to indicate fairly typical practice. The alloys containing cerium are more critical in terms of optimum conditions since the criterion for these materials is creep resistance at temperature rather than optimum mechanical properties at room temperature. It will be seen that whereas British practice with the cerium-zirconium alloy (DTD 728) is to give a single low temperature stabilizing treatment, American heat treatment practice for similar alloys EK30A, EK41A, favours a solution heat treatment at 1050°F. (565°C.) followed by ageing at 400°F. (205°C.).

With all alloy the length of solution heat treatment will be influenced by the maximum section of casting to be treated, heavier sections requiring longer times. On the other hand, gravity die (permanent mould) castings require slightly shorter soaking periods due to the smaller size of the particles of eutectic which have to be dissolved. Further, salt baths have a higher efficiency of heat transfer than have air furnaces. A safe rule is to establish the cycle that gives satisfactory results on the thickest sectioned casting normally treated with the maximum safe load, and then to standardize on it.

REFERENCES

[1] F. A. FOX and E. LARDNER. *J. Inst. Metals* (1943), **64**, 373–96.
[2] R. S. BUSK and R. E. ANDERSON. *Trans. A.I.M.E.* (1945), **161**, 278–90.
[3] T. E. LEONTIS and H. E. ELLIOTT. *Trans. A.I.M.E.* (1951), **191**, (2), 120–4.
[4] R. J. M. PAYNE. *J. Inst. Metals* (1950–1), **78**, 147–68.
[5] British Patent 254,741.

[6] Société Générale du Magnesium. *Le Traitement Thermique des Alliages de Magnesium*, p. 10.

[7] American Foundrymen's Association. *Magnesium Alloys Foundry Practice*, p. 13.

[8] British Patent 539,861.

[9] U.S. Patent 1,574,289.

[10] British Patent 452,390.

[11] A. T. PETERS, R. S. BUSK, H. E. ELLIOTT. *Trans. A.I.M.E.* (1945), **161**, 291–312.

CHAPTER 9

The Inspection of Magnesium Alloy Castings and Notes on Common Defects

DEFECTS in magnesium alloy castings found in the inspection stages may be grouped according to the deficiencies in the production processes that caused them. Following the descriptions of processes given in earlier chapters, specific causes for scrap can now no doubt be inferred, and therefore this chapter may possibly be regarded as redundant. Nevertheless, a brief recapitulation of such facts, collected in one place, should not be without its value.

Mechanical tests on separately cast test bars are widely used as a routine check on metal quality and as an acceptance test by the customer. The test bars used vary somewhat in different countries; a parallel bar which is subsequently machined to shape is in common use in Great Britain. In the U.S.A. and in many Continental countries, test bars are cast to the required shape and tested in the as-cast condition.

Significance of Mechanical Tests

Test bars may be produced from a metal mould, or from a sand mould. For control work on magnesium alloy, sand moulds are of advantage; for metal moulds may obscure the results of lack of process grain refining; further, owing to the quick chilling, microporosity in the bars will be at a minimum.

Low test results on tensile testing may indicate incorrect or inefficient melting methods. The fracture should be examined carefully for evidence of grain size and cleanliness of the fracture. A characteristic of magnesium and its alloys is that porous areas tend to be discoloured, the tint varying from pale straw yellow to brown or black according to whether the porosity is slight or severe. While such discoloration can be seen in as-cast structures, it is intensified by thermal treatment; what is barely perceptible in the as-cast condition is unmistakable on metal that has been heat treated for six hours at about 400°C. (750°F.). When fracture testing of actual castings is applied for the determination of soundness, castings should always first be given at least this treatment in order that minor defects are clearly discernible.

With the full knowledge on the subjects of grain refining and porosity detailed in the appropriate chapter, the incidence in test bars or broken castings of large grain size and porosity may throw suspicion on the melting process, particularly if found in test bars. It must not be supposed, however, that all instances of micro-porosity are due to incorrect metal treatment, for shrinkage of the same proportions may still be caused by lack of feeding, that is, from incorrect moulding methods. Several foundries, particularly in the U.S.A., have reported that following the introduction of degassing by chlorine, failures of test bars from porosity became non-existent. Experience seems to indicate that such treatment provides an effective means of eliminating porosity due to gas, thus enabling porosity in castings to be ascribed solely to poor feeding. Porosity in a sand cast test bar, which may be expected from its design, to be adequately fed, may, therefore, now be taken to indicate lack of degassing of the molten metal.

Visual Inspection of Castings

Visual inspection before despatch is an accepted stage before the final release of the castings to the customer. If carried out by an experienced person it can give a good indication of the quality of the castings since surface defects are often an indication of more serious defects in the main body of the casting.

Deficiencies in moulding sands may be the cause of casting defects. It will be remembered that inhibiting substances are incorporated with the moulding sand and some of the substances act by the means of the production of an inert atmosphere within the mould as the metal is poured. If, therefore, the texture of the sand is not open enough to allow these gases to be pushed forward and escape in front of the flowing metal, the possibility exists that these gases may be trapped within the casting. When this occurs, due to the use of sand of too close a texture, that is, of too low a permeability value, castings are produced which, while they appear sound visually, nevertheless have innumerable small blow-holes present just beneath the surface

(*Fig*. 40). These blow-holes are of silvery appearance, indicating that no oxidation has taken place. The cure for this defect is obvious.

Because of the necessary high permeability of the sand required, there is a tendency for the surface of magnesium alloy sand castings to be rough, but much may be done to overcome this defect by careful estimation of the grain size and shape of the silica sand used. Permeability is a function of the distribution of grains of regular size as much as of large grain size as a separate factor. In this connexion of surface appearance, the view is held in some quarters that a gravity die casting 'makes' better after the mould surface carries a rough coat of wash. The question has not been completely resolved, but if it has any foundation in fact, it is obvious that the die surface should be the finest possible commensurate with producing castings successfully; in other words, some compromise between finish and production requirements must be arrived at.

Blemishes of the cast surface, as distinct from the above, are caused by insufficient inhibitor content of the sand. Reaction between molten metal and moisture and possibly silica of the sand, takes place first at

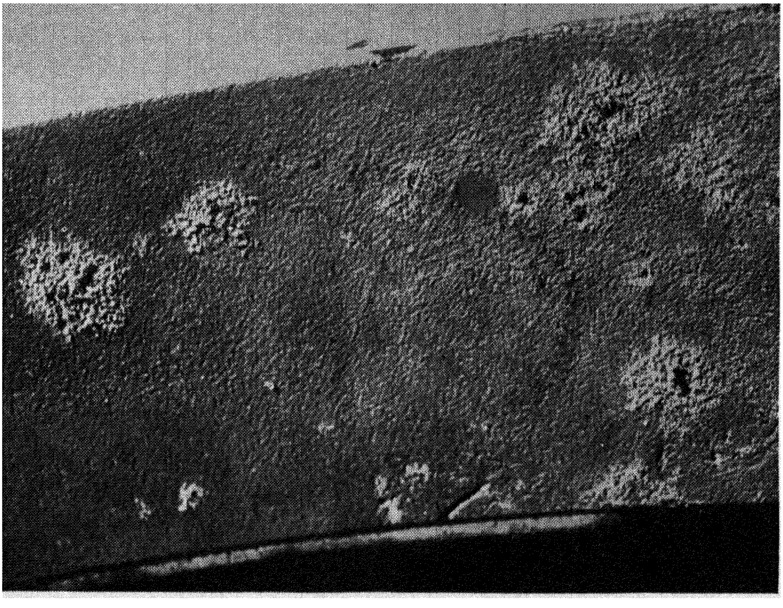


***Fig*. 36. Flux inclusions on surface of magnesium gravity die-casting.**

positions where cross-sections of the casting are large; the first signs of 'sand attack' may be expected to appear on bulky risers. Inspection as such will, therefore, seldom meet this defect, as its appearance at knockout stage will be the signal for the foundry control staff to take remedial action.

A defect which is seldom met with these days is local corrosion caused by flux inclusions. A typical example of these is illustrated in *Fig.* 36 which is from a die-cast component, and the small white patches due to flux inclusion are clearly visible. If flux inclusions are suspected, exposure to steam for about six hours will accelerate the corrosion reaction sufficiently to confirm the presence of flux compounds. Such is the reactivity of flux that inclusions may even be revealed by weathering the casting in a normal atmosphere for about twenty-four hours.

Crack Detection

It is often difficult to determine the presence of cracks visually, and in this case recourse may be made to the use of one of the crack detection methods. There are the usual shop methods in which the crack is revealed by warming the casting slightly, followed by application of some oil. After removing excess oil, french chalk is powdered on to the casting and then the excess chalk is shaken or blown off. Cracks may be revealed where the chalk has been held by the oil in a crack. A similar method is the etching of castings in an acid pickle, such as the chrome-nitric pickle referred to in Chapter 10, or a 5 per cent sulphuric acid solution; in which case the rate of attack is sufficiently different at the surface of the crack to show it clearly when the casting has been washed and dried.

A more elaborate method consists in the use of the immersion of a casting in heated organic liquid containing a fluorescent compound. The solution seeps into pores and cracks; sufficient fluorescent matter is held even after the casting is washed in a suitable bath, consisting of an organic solvent. When dry, the casting is examined in a dark room under the radiation from an ultra-violet lamp, cracks showing up clearly as fluorescent lines, while surface porosity is revealed as fluorescent 'smudges'.

Cracking at sharp changes of section is often due to constraint during solidification and if this becomes a characteristic defect (*Fig.* 39) it may be assumed that ramming has been too intensive or that the core is too hard and has too much core binder present resulting in insufficient collapsibility of the core as the hot casting contracts around it. It is, therefore, important that the foundry use core sand mixtures that are only just hard enough after stoving for foundry handling.

Cracks in gravity or pressure die-castings are often due to the same fundamental reason indicated above, that is, constraint during solidification (*Fig.* 37). This may be verified by a fracture test where, as indicated above, discoloration will confirm that the crack has been formed at high temperatures. Many castings of thin section and extensive area are prone to distortion, either at knockout from a sand mould or during removal from the die. The presence of cracks in die-castings should be an urgent indication of the need to make suitable changes in foundry technique or die design to avoid its recurrence.

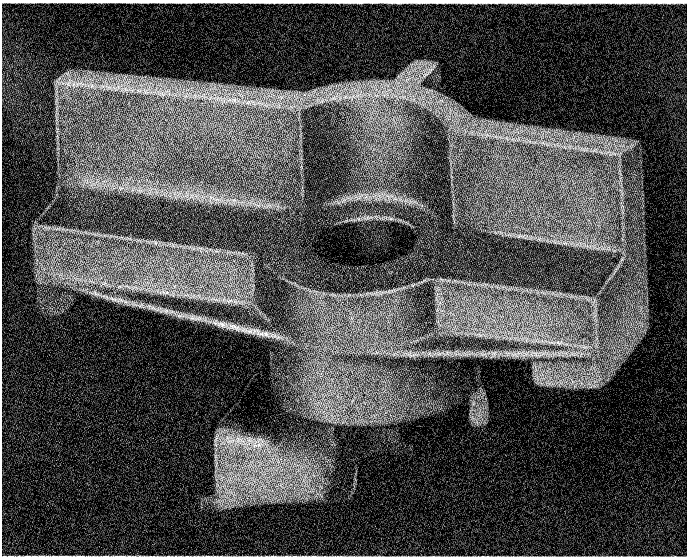


Fig. 37. Crack in corner of gravity die-casting.

Defects Arising in Heat Treatment

Defects arising from heat treatment are due, in general, to the use of too high a temperature or to distortion by the sagging of thin unsupported sections. If the temperature exceeds the eutectic temperature, the castings will be completely ruined since fusion of the eutectic will lead to bleeding at the surface and the presence of voids within the mass. An example of the appearance of a grossly overheated section from a casting is shown in *Fig.* 38. Nothing can be done if this occurs; the castings are scrap. Distortion is a serious problem but it has been shown that proneness to distortion increases with rising temperature up to the maximum of the eutectic temperature of course. By the adoption of longer periods, treatment at a lower temperature will often be found to overcome distortion, whereas treatment of the same castings at higher temperatures will lead to badly distorted castings. It is always troublesome and expensive to rectify distortion by straightening and it may in some cases be impossible to do so satisfactorily.

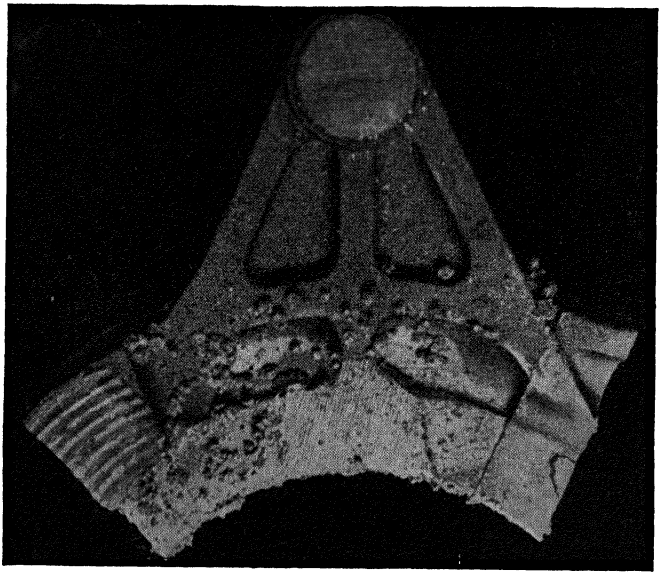


Fig. 38. Blisters on surface of section of sand casting due to overheating in heat treatment.

Use of Radiography

Due to the close association in the past of the growth of magnesium technology with the requirements of the aircraft industry, radiography has probably been more widely applied as an inspection method to magnesium castings than to components in any other method. Whilst aeronautical inspection authorities will continue to make certain demands on the use of radiography as an acceptance test for important stressed castings, it is important to consider its application over a broader field. It is obvious that there are many commercial applications for magnesium castings which are as yet undeveloped but the long-term expansion of the magnesium foundry industry and its general well-being depend upon increasing the production of castings for these fields. Radiography should therefore be regarded as a tool to help provide the customer with consistently sound castings at an economical price.

Two forms of radiological examination are employed; the use of a fluorescent screen and radiography. In the former, the casting to be examined is placed between the X-ray source and a fluorescent screen which radiates visible light when subjected to X-ray emission. The result of this is that a 'shadow' of the casting is formed on the screen. The rays from the source pass through the casting in varying amounts, dependent upon the thickness of the metal to be penetrated. Thus the 'shadow' is not of uniform darkness but varies with the section of the casting. The thinner sections, offering less resistance to the X-ray, appear lighter than the thicker sections. This is not a critical form of examination but is good enough to detect such obvious internal flaws as blow-holes. It should not however be used to make a decision on any other sort of defect, even if there is sufficient evidence to believe, from screening, that such defects are present. Such suspected castings should be radiographed. Screening should be carried out for short periods only as it is very fatiguing to the eyes. Also great care must be taken to protect the operator from the rays. Never, in any circumstances, must the tube point directly at the operator, but the image must be reflected by means of mirrors. Even if no defects are found by screening, it is not proof that the casting is free from defect.

In radiography the screen is replaced by a photographic film which is far more sensitive to X-rays, which should be produced from a fine focus tube (*Fig.* 41). This can only be obtained from a unit of fairly low power. Also a fine-grain film of high contrast must be used to show the minute flaws peculiar to magnesium. By using this method, minute flaws can be detected by a skilled interpreter of the resulting radiograph. Such defects as small amounts of porosity, excessive grain size or small oxide inclusions can be definitely detected.

These flaws may not always warrant the scrapping of the casting, but by using a set technique in radiographing any particular part, and by examination of the fractures of castings which have been radiographed and have shown some defects, a standard can be set by which subsequent castings of that particular type can be scrapped or passed as the radiograph indicates.

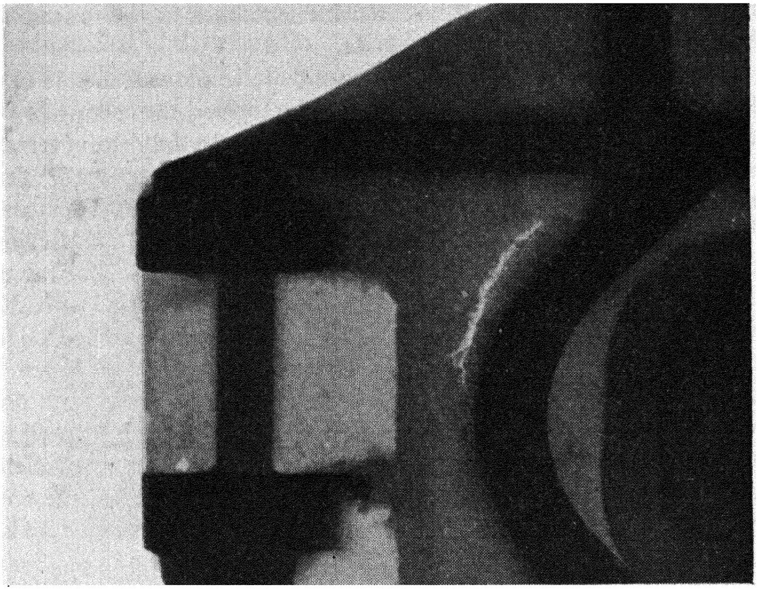


Fig. 39. Print from radiograph showing hot tear.

Unfortunately, as any particular exposure in making a radiograph can only be ideal for one thickness of metal, and very few castings are of only one thickness, one has either to make a separate shot for each section of the casting or compromise by exposing for the average thickness. This can only be decided by the use to which the casting is ultimately to be put. If a section is to be highly stressed then there should be a highly critical radiograph made of that section.

Radiography is an expensive method of inspection and its use will therefore tend to be limited to the development stages during which the foundry is developing the best casting technique to ensure a consistent standard of quality. Radiographs should be taken of the prototype castings and interpreted in conjunction with break-up tests of the suspected defective areas. Once a satisfactory technique has been established, the first batches of production castings should preferably all be checked by screening and a percentage by radiography. When the satisfactory production technique has been achieved it should be standardized and recorded in an appropriate central file.

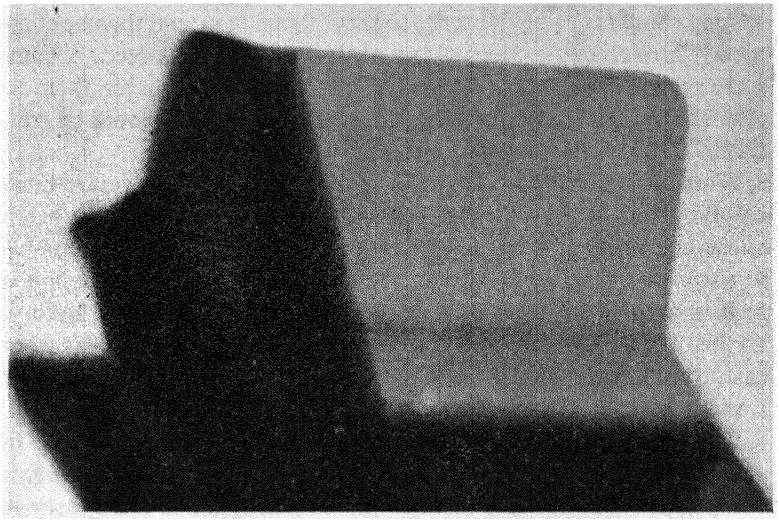


Fig. 40. Print from radiograph showing blow holes due to low permeability of moulding sand.

The interpretation of a radiograph requires much experience and practice since indications of serious flaws in the radiographed object, although visible to an experienced interpreter, can often hardly be detected by an inexperienced person. A good interpreter should have a knowledge of metallurgy and engineering since a radiograph can only be interpreted correctly if he knows exactly the purpose for which the radiographed component will ultimately be used. The deciding factor on whether the casting should be scrapped or not should be whether the casting is suitable to do the job for which it has been designed, and give the required factor of safety. With this in mind, it is possible to set a standard for each particular component.

When a new casting is received a drawing should be obtained from the designer clearly showing the sections subjected to high stress and also a drawing showing the importance of the casting as regards the final structure. The highly stressed sections should be given a critical radiographic examination in all the subsequent castings. The interpreter should decide how many shots should be made and work out the required exposures. When the casting has been radiographed and any corrections in exposure made, the radiograph or radiographs should be examined. Any defects revealed should be noted and the casting should then be fractured to show them. It should then be completely broken and examined and any further defects noted. A complete report should then be sent to the foundry to enable them to alter the casting technique to give sound results. This should be continued until good castings are produced.

When a particular part number is in production, a standard must be set by which to pass them. This is done by radiographing a batch of castings according to the technique evolved as above, and baking to show any flaws revealed in the radiograph. The worst casting is broken first, and if the interpreter decides that this is unsatisfactory, he then breaks the next and continues until he reaches a satisfactory casting. When this is done, the radiograph of that casting is used as a standard for subsequent castings.

This method applies to castings which take little or no stress. In cases of highly stressed castings, such as those used in critical aircraft components, only perfect castings can be accepted. All these castings are normally required to be radiographed and at least one casting from each batch fractured as a check on the radiographic examination.

This is essential because, as pointed out previously, a critical radiograph examination of every part of a casting as a routine procedure, is seldom a convenient proposition. It would entail too many shots, and in some cases is not even possible. If a casting, one of a batch, has been radiographed and no defect observed, and on fracture a flaw is revealed which would have made it unsatisfactory for its designed use, then either the remainder of the batch have to be radiographed with special reference to the defective area or they all have to be scrapped.

In the case of percentage radiographic examination, the worst of the radiographed castings must be satisfactory, otherwise there is no guarantee that all the unradiographed castings are acceptable. Should there be any doubt, the casting should be fractured and a decision made. Should it be unsatisfactory the whole batch should either be radiographed or scrapped. The only alternative is to notice if there is any surface evidence which might have given some indication of the defect. It is usually safe then, to increase the percentage radiograph, and if no more trouble is detected, to pass the batch.

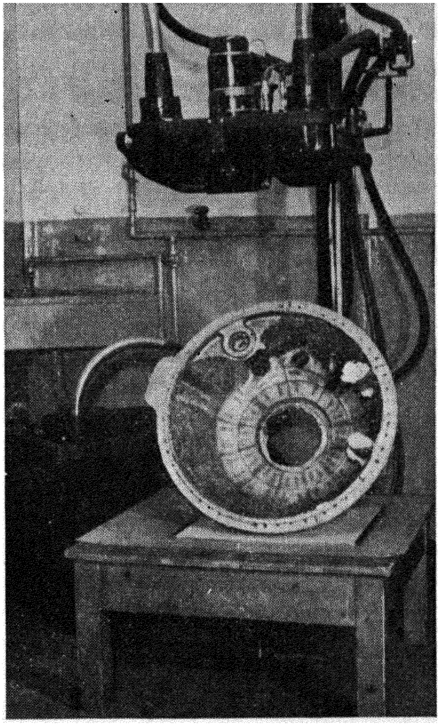


Fig. 41. Magnesium sand casting being subjected to radiological examination using 140 kV. X-ray set.

If any particular casting has shown itself to be free from defects over a considerable number made, then the percentage examined can be considerably reduced, but this will rarely fall below 10 per cent where a really high standard is required.

These remarks are intended as a guide to cover all requirements and due consideration must be given in all cases to the function which the casting performs in the finished assembly, the degree of consistency which can be expected, and the economies of the job. In most commercial work, radiography intelligently applied in the development stages, will yield dividends in terms of consistently sound castings when quantities are sufficient to justify the initial cost of the work. To the general user, the reliability of magnesium castings assured in this manner will prove a valuable although indirect selling point.

CHAPTER 10

Surface Treatment

MAGNESIUM CASTING ALLOYS are used in a variety of applications and whilst in many instances the assembled components can be used without surface treatment, there are a wide variety of conditions where some finishing operations are required either to provide a decorative appearance or for additional corrosion resistance. Before outlining surface finishing processes it is useful to briefly restate the main characteristics of magnesium in various environments.

The metal, although one of the most chemically active of common metals, is not particularly susceptible to atmosphere corrosion in industrial and rural atmospheres. Tests made by the authors on machined magnesium alloy test pieces exposed to a moderate industrial environment over five years, showed pitting only to the depth of about 0·005 in. whereas mild steel specimens exposed at the same time had corroded to the extent of a loss of 0·025 in. This experience has been confirmed by American tests on a wider range of alloys over a ten-year test period.

In marine atmospheres magnesium is more affected due to the presence of chlorides in the salt spray but much depends upon the impurities present. Work by Nelson and Hanawalt,[1] which has subsequently been largely confirmed by other investigators, showed that for maximum corrosion resistance the iron content should be kept below 0·002 per cent in alloys containing aluminium, the nickel content 0·001 per cent and copper 0·010 per cent.

It has been reported [2] that tests at the R.A.E., in which controlled purity magnesium alloy specimens were sprayed three times daily with sea water, showed them to be very little affected, whereas specimens of normal iron content showed pronounced corrosion after six months. Tests made by the Dow Chemical Co. at a site 80 ft. from the ocean at Kure Beach, North Carolina, confirmed this, in that over a four-year test period only slight loss in elongation was found on controlled purity casting alloys, whereas specimens made from alloys of normal purity had been badly corroded in the period losing about a third of their original strength.

Magnesium alloy castings have given satisfactory service in the damp atmospheres of textile mills when used for spools, beams, bobbins etc., and when used for electric hand tools sold in all parts of the world. Generator cap parts used in the pre-war Ford (U.S.A.) cars have given very satisfactory service. In some American bakeries magnesium delivery cabinets have been in use for up to ten years, and the good behaviour of the material when cleaned with alkali cleaners has proved it superior to the galvanized steel previously used.

However, the oxide formed on solid magnesium in the atmosphere is not a continuous fully protective film (already noted in regard to molten magnesium) as is the case with aluminium. For the more severe environments, or to preserve or enhance the surface appearance of the metal, various finishes are resorted to, used by themselves or as a base for a protective organic finishing system.

Chemical Treatments

One of the oldest chemical treatments used is the nitric-dichromate dip known either as the 'chrome-pickle' or 'Dow No. 1'. The composition and treatment conditions are summarized in Table 14. Owing to the high rate of attack it should not be used on machined parts where close tolerances are required since metal loss of 0·00025 in.–0·001 in. may result. The film is of a pleasing golden-bronze colour. It has been used to provide some degree of protection to castings stored in damp conditions, and is also useful as a measure of detecting cracks in die-castings since staining occurs in their vicinity.

For finished machine parts the process which has been widely used in Great Britain for a number of years on aluminium-containing alloys is the R.A.E. thirty-minute chromate bath which is similar to Dow No. 3 process. It is a dilute bath containing small amounts of ammonium sulphate, sodium dichromate and ammonia dichromate, with ammonia or chromic or sulphuric acid additions to maintain the pH value at approximately 6·0. The bath is operated at boiling point and, as the name of the process indicates, thirty minutes' treatment is required, after which it is rinsed in cold and then hot water. The coating produced is black on alloys containing around 10 per cent aluminium but is straw to brown colour on most other alloys.

In elementary terms a pH value of 6·0 means that the solution is only very slightly acid so that the attack on the metal is very slight. The control of this acidity is very important since the optimum pH value varies for different alloys, a figure of about 5·8 being better for the aluminium alloys, whereas about 6·3 will yield better results on the 1·5 per cent manganese alloy. The alloys containing zirconium give satisfactory results at pH 6·0 but a chrome-manganese bath detailed later is preferred in Great Britain for these materials.

Before immersion in the bath, the component must be clean, and ten to fifteen minutes in a boiling solution of 2–5 per cent caustic soda is satisfactory; this is followed by cold water rinsing and then transfer to the chromate bath. Control of the chromate bath is essential although a weekly analysis may be adequate. The pH can be controlled by sulphuric acid additions; 2½ fluid ounces of concentrated sulphuric acid added to 100 gallons of solution lowers the pH by 0·1. If the pH must be raised then 8 fluid ounces of 0·880 ammonia will increase it by 0·1. The chromate and sulphate contents of the bath calculated as chromic acid (CrO_3) and sulphuric acid should be maintained between 1·75 and 2·5 per cent. When the sulphate figure exceeds the maximum figure the bath should be discarded.

In the U.S.A. it is customary to precede the R.A.E. bath by dipping in a 15–20 per cent hydrofluoric acid solution for five minutes at room temperature, thoroughly rinse and then with the fluoride film so formed, immerse in the boiling R.A.E. bath for forty-five minutes. This combination, referred to as Dow No. 8, gives good protection and is a satisfactory paint base and the coating is rather more abrasion resistant than the standard R.A.E. film. A further modification is to galvanically anodize for thirty minutes after treatment in the hydrofluoric acid dip, using the R.A.E. bath at 50°C.–60°C. (Dow No. 9). The components are coupled to steel cathodes of sufficient size to give a current density of 10 amps./sq. ft.

One of the most popular baths in the U.S.A. is Dow No. 7, in which the components are first immersed in the hydrofluoric acid dip, produced by diluting one volume of 48 per cent hydrofluoric acid with two volumes of water, followed by treatment for forty-five minutes in a boiling 10–15 per cent sodium dichromate solution. The pH of the dichromate bath should be maintained at around 4·5–5·0 and the dichromate content should be kept within the limits specified and certainly should not be allowed to fall below 8 per cent by weight.

Careful rinsing after the hydrofluoric dip is essential since the presence of 0·25 per cent of the acid is sufficient to cause the bath to function unsatisfactorily.

In Great Britain a more recently developed bath which operates cold is one consisting of 10 per cent sodium dichromate, 5 per cent magnesium sulphate, and 5 per cent manganese sulphate. It can be used at room temperature with a preferred immersion time of two hours, although this can be appreciably reduced by warming the bath so that at 75°C. only fifteen minutes is required. Control is achieved by means of sulphuric and chromic acid additions, with the pH being maintained at 5·0–5·5. It has been developed particularly for the zirconium-containing alloys which tend to give a slightly mottled film when treated by the R.A.E. bath. The life of the bath can be extended by additions of up to 5 per cent manganese sulphate and the pH adjusted by additions of sulphuric acid.

All the above treatments give films of brown to black in colour, except for the chrome pickle which is brassy in appearance. The decorative value of these coatings is limited, although their protective value is good, probably due to the presence of chromium hydroxide in the film. If clear or semi-opaque coatings are required which can be subsequently dyed, there are a few baths which give satisfactory results although experience with them is limited.

A simple bath, developed by Magnesium Elektron Ltd.,[3] consisting of 20–30 per cent caustic soda and 2–10 per cent sodium sulphate operated at boiling point, gives a transparent film which will absorb dyestuffs. A phosphate film is produced by a patented process of Yorkshire Dyeware and Chemical Co.[4] which uses a solution of 20 per cent phosphoric acid, 30 per cent water, 50 per cent methylated spirits with 0·5 per cent of a wetting agent. The components are immersed for five minutes at room temperature, rinsed and then dried for thirty minutes at 180°C. Neither of these processes has been used commercially.

Anodizing Treatments

In the United States the Dow No. 12 caustic anodizing bath has had some limited use for coloured coatings. The bath composition is shown in Table 14 and it is operated at 170°F. (77°C.) and after five minutes' immersion in the bath, the components are anodized for fifteen to twenty-five minutes at 15–20 amps./sq. ft. After anodizing,

TABLE 14

Summary of Chemical Surface Protection Processes

Bath	Composition	Conditions	Remarks
Chrome pickle (Dow No. 1)	Sodium dichromate 1½ lb. Nitric acid 1½ pts. Water 1 gal.	½–2 mins. at 21–32°C. (70–90°F.)	Tanks material aluminium, stainless steel or rubber-lined
R.A.E. bath (Dow No. 3)	Ammonium sulphate 3 lb. Ammonium bichromate 1½ lb. Potassium bichromate 1½ lb. Ammonia (0·880) ⅖ pt. Water 10 gal.	30 min. at 100°C.	Mild steel tank. Regular checks on pH necessary (pH≃6·0)
Dow No. 8	1. Hydrofluoric acid 1½ pt. Water 1 gal. 2. As R.A.E. bath	5 mins. at room temperature 45 mins. at 100°C.	Lead or rubber-lined tank
Dow No. 7	1. Hydrofluoric acid 1 lb. Water 2 gal. 2. Sodium dichromate 1 gal. Water 1 gal.	4 mins. at room temperature 30–45 mins. at 100°C.	Lead or rubber-lined tank Steel tank. Solution pH 4·5–5·0
Chrome manganese (M.E.L.)	Sodium dichromate 1 lb. Manganese sulphate 8 oz. (crys.) Magnesium sulphate 8 oz. Water 1 gal. (+ 1% Teepol optional)	2 hrs. at room temperature, or ½ hr. at 55°C. or, 15 mins. at 75°C.	Steel, aluminium or glass-lined tank. pH 5·2 (4·0–6·0)
Dow No. 12 (caustic anodize)	1. Caustic soda 2 lb. Ethylene glycol 0·55 pt. Sodium oxalate ⅓ oz. Water 1 gal. 2. Ammonia (·880) 1¼ fl. oz. Water 1 gal.	5 mins. immersion then anodize for 15–25 mins. at 75–80°C. at 15 amps./sq. ft. left in bath further 2 mins. 2. Water rinse, then given either neutralizing seal or are first dyed and then sealed for 15 mins. at room temperature	Tank should be steel or magnesium Neutralizing tank may be steel, aluminium or lead-lined

the articles are rinsed in a dilute ammonia solution, containing 1¼ fluid ounces per gallon, and then placed in a boiling dye bath to which 1 ounce of boric acid and 1½ ounces sodium chromate per gallon is added, in addition to the dyestuff which will usually be at a concentration of ⅛–½ ounce per gallon. The acid free dyes, such as are used for anodized aluminium, will usually be satisfactory for dyeing such coatings.

From the above account it will be evident that the colouring of magnesium is an art that is still in an early stage of development and the coatings available are rather thin and not particularly resistant to abrasion. The best results are produced with the anodized coatings particularly as far as wear is concerned. Whether it will be possible to produce thicker and abrasion resistant coatings which can also be dyed remains the subject of further work but two recently announced processes are capable of giving thick abrasion resistant coatings. The harder of the two is the film produced by the HAE process (derived from the initials of its inventor H. A. Evangelides).

The patent[9] for this process has recently been published, and the following composition range is given together with an example of a composition found satisfactory.

	Range *gm./litre*	*Example* *gm./litre*
Potassium manganate	1–60	20
Potassium fluoride (anhy.)	1–300	35
Trisodium phosphate ($12H_2O$)	10–300	35
Potassium hydroxide	20–130	100
Aluminium hydroxide (dried gel)	1–100	30
Bath temperature	−10°–+65°C.	20°–30°C.
Current density	5–500 amps./ft.^{2}	15 amps./ft.^{2}
Time	Up to 90 mins.	60–90 min.

The current is supplied from an A.C. source and the voltage is progressively increased to maintain the current density reaching 80–85 volts at the conclusion of the treatment. A coating of 0·001 in. is produced in 60 minutes' treatment. It is stated that for maximum abrasion resistance a post treatment for half minute in a 16–25 per cent hydrofluoric acid solution followed by ageing at 70°C. (170°F.) eliminates much of the moisture in the film and increases its abrasion resistance.

A further treatment which has been announced[10] is the Cr-22 treatment, consisting of

Chromium trioxide	25 gm./litre
50 % Hydrofluoric acid	50 ml./litre
30 % Aq. ammonia	170 ml./litre
Temperature	70°9–5°C.
Current density	15 amps./ft.^{2}
Voltage	Up to 380 v.
Time	12 mins.

This treatment would appear to have the disadvantage of requiring very high voltages to produce the coating which is 0·001 in. thick, and at present there is insufficient experience available to indicate whether it has any over-all advantage over the H.A.E. process.

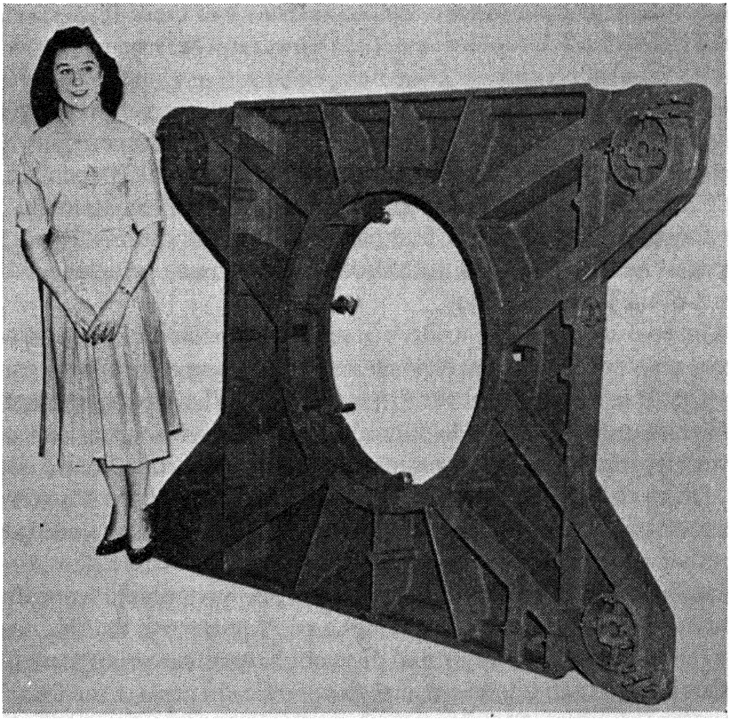


Fig. 42. Large casting treated by HAE process for maximum corrosion resistance. (*Brooks & Perkins Inc.*)

According to published information the film is of a brown colour, varying from oatmeal to a fairly deep brown, depending upon thickness and bath conditions. The hardness of the coating is 7–8 on the Moh's scale and is thus comparable with the hard anodized coatings obtainable on aluminium alloys. The dielectric strength of a coating slightly more than 0·001 in. (1 mil.) in thickness was 550 volts at 60 cycles. The corrosion resistance of the standard coating is quite good with little corrosion evident after 200 hours' salt spray, but sealing in wax or with a zinc chromate phenolic resin primer produces an outstanding increase in protection and satisfactory performance after 13,000 hours salt spray test has been reported.

As might be expected, such a coating is rather brittle although it has a small but definite degree of ductility. The opinion has been expressed that the bath requires rather more current consumption per unit of film thickness than other processes and there is a tendency for the solution to heat when a well-loaded tank is used, thus making some provision for cooling essential. However, for wear resistance it has no equal at present.

Another recent anodizing process is the Dow 17 treatment, which employs an electrolyte containing ammonium hydrogen fluoride, sodium chromate, phosphoric acid and water. The bath is operated at 70°C.–80°C. (160°F.–180°F.) and anodizing for fifteen minutes at 20 amps./sq. ft. is a typical treatment for D.C. conditions. It is also permissible to use A.C. but the anodizing time must be extended because of the lower efficiency.

The coatings are light to dark green in colour and have good salt spray resistance particularly when sealed with wax or similar organic sealant. It is claimed that the fire resistance of the Dow treatment is higher than for the H.A.E. film although its abrasion resistance is lower. In other respects, including good paint adhesion, the two coatings have roughly similar properties. Modification of the above two processes have also been reported, where thinner films are adequate or other adjustments of the coating characteristics required.

In this country Magnesium Elektron Ltd. have developed a fluoride anodizing bath[7] which provides a good protective fluoride coating. The coating is not thick and does not have outstanding corrosion resistance; in fact, it is sometimes the practice to replace the fluoride layer by a chromate film. Its real advantage is that it is a most effective means of ensuring a completely clean surface free from impurities.

Experience has shown that it is often difficult to remove surface contamination, such as small iron particles, from tools used in dressing the casting or metallic shot, and the fluoride anodizing process has proved very effective as a means of removing it.

Prior to anodizing, any loosely held grit should be brushed off, and if any grease is present it should be removed by vapour cleaning, caustic soda pickling or similar treatment. The flouride bath is a 10 per cent aqueous solution of ammonium biflouride in water used at around room temperature and not exceeding 30°C. The work should be fixed in pairs on alternate electrode bars so that there is approximately the same area on each electrode. The work should not be less than 9 in. below the surface, and all clamps and jigs immersed in the electrolyte must be a magnesium base material. Alternating current is applied, the voltage being progressively increased to 90–120 volts. The initial current flow is high but rapidly falls off, and the treatment is continued for ten to fifteen minutes or until the current falls to less than 5 amps/sq. ft. The current is then switched off, and the articles washed, preferably in hot water, and dried.

The treated articles should have a uniform clean white or pearly-grey appearance. Dark areas in recesses indicate entrapment of gas, whilst an etched appearance indicates too low in bifluoride which should be within 5–15 per cent. Pitting of the surface may be due to the presence of chloride. Protection by sealing of the coating in an epichlorhydrin resin, subsequently stoved, is recommended.[8]

Mechanical Polishing

For many purposes, a polished finish may be desired either for subsequent chemical treatment and painting, for protection by a clear lacquer, or as a self-finish possibly in conjunction with the chrome pickle. Polishing technique for magnesium castings follows that used for aluminium with slight modifications. The following are the materials and polishing speeds appropriate to the various stages in polishing:

After polishing it is necessary to remove any traces of polishing compound or grease if a clean surface is to be produced: this is essential if chemical treatments are to follow. Trichlorethylene vapour or emulsion cleaners are very satisfactory for removing grease and oil but not effective in moving polishing compound and whilst a straight 2–5 per cent boiling caustic soda solution is reasonably good,

Operation	**Abrasive**	**Wheel**	**Peripheral Speed (ft./min.)**
Roughing	60–120 grit Alundum or Carborundum	Felt, glued canvas or sheepskin	3,000–5,000
Greasing	150—flour	Built-up cotton canvas or muslin cloth buffs	4,000–6,000
Buffing	Tripoli paste	Sewed buffs (74–82 count) canvas Canton flannel, muslin etc.	6,000–8,000
Colouring	Vienna lime	Canton flannel buffs	8,000–12,000

the contaminants tend to float on the surface as scum. The following two mixtures are rather more satisfactory:

(A)	Trisodium phosphate	3 oz./gal.
	Sodium carbonate crystals	6 oz./gal.
	Soft soap	⅛ oz./gal.
	Used at boiling point.	
(B)	Sodium carbonate	3 oz./gal.
	Sodium hydroxide	2 oz./gal.
	Soft soap	⅛ oz./gal.
	Used at boiling point.	

Mixture (A) can be used as an electrolytic cleaner if the soap is omitted; the work is made—the cathode and the current density is 10–20 amps./sq. ft. with a bath temperature of 70°C.–80°C. (160°F.–180°F.) and three to five minutes' treatment is required. Where the straight immersion baths are used, ten to fifteen minutes' soaking is desirable.

If castings have been sandblast they should be acid pickled before further treatment is carried out, unless the as-cast surface will be completely removed by machining. The pickling treatment removes any particles embedded in the surface which might subsequently become centres of corrosion. Often the chrome-nitric pickle will prove suitable but if another protective system is to be subsequently applied it will be better to use a nitric-sulphuric pickle such as 8 per cent nitric acid, 2 per cent sulphuric acid, immersing the components for ten to twenty seconds with the bath at room temperature.

Bright Dipping

A bright surface can be obtained by treatment in a 75 per cent phosphoric acid solution, although the appearance is one of diffuse rather than specular brightness. With die-castings this treatment is useful in removing the surface skin which can give rise to lack of uniformity or poor coatings when given a chemical treatment. A rather better, more specular bright finish can be obtained in the following bath (Dow No. 16).

Chromic acid	15 per cent by weight
Sodium nitrate	25 per cent by weight
Magnesium fluoride	0·05 per cent by weight
Water	Remainder

One to two minutes at 21°C.–32°C. (70°F.–90°F.).

The treatment is followed by a cold and then a hot water rinse. An addition of 0·05 per cent acetic acid will produce a bright 'frosted' finish. Although the treated parts will remain bright for many months without protection, covering with a clear lacquer is advisable if the bright finish must be preserved for longer periods.

Painting

As already indicated, chemical treatments are often used to provide a good 'key' or bond between the metal and subsequent paint coatings. Several primers have been developed which give good adhesion when applied direct to the clean metal surface. The best known of these are the various proprietary 'etch' or 'wash' primers which are based on polyvinyl butyral resins containing zinc tetroxychromate to which is added a second solution containing phosphoric acid. Careful control over the mixing is essential since the water and acid contents are critical. Stoving is necessary to obtain the best results although moderate results can be obtained from air drying. These coatings should be regarded as pre-treatments and not as primers in the strict sense of the word.

Good adhesion can be obtained with epichlorhydrin resins and the stoved coatings have high hardness. These resins can be polymerized by various agents so that other organic groups can be incorporated into the chain. The epichlorhydrin-bisphenol types are the most widely used at present but a rather high stoving temperature is required.

Paints of the more conventional type such as those based on alkyds, modified phenolic resins etc., give good adhesion when applied over chemically produced films. Where protection against corrosion is important, pigmentation of the primer with zinc chromate or tetroxychromate is standard on account of its corrosion inhibiting properties. Undercoats and finishing coats of the usual synthetic types are quite satisfactory; the only limitation on pigmentation of paints being that lead pigments, or graphite in other than small amounts, should not be used. Iron oxide (red oxide) should be avoided in primers.

Plating

For some years the problem of plating on magnesium had been an insuperable one due mainly to the electrochemical position of magnesium, and its strong tendency to form hydroxide films in aqueous solutions which interfere with plating. In Great Britain no commercial plating has yet been undertaken although various processes have been patented.

It is of some interest to give some details of a process developed by H. K. Delong[6] of Dow Chemical Company which has been used commercially for the plating of several hundred thousand parts, mainly die-castings. (*Fig.* 43.) After polishing, the parts are degreased either by vapour cleaning only or followed by alkaline degreasing. This is followed by a pickling treatment consisting of fifteen seconds to three minutes' immersion at room temperature in either of the following baths:

(A)	Chromic anhydride	(CrO_3)	280 gms./litre
	Nitric acid	(70% HNO_3)	25 mils./litre
	Hydrofluoric acid	(48–52% HF)	8 mils./litre
(B)	Phosphoric acid	(85% H_3PO_4)	No dilution

If the slightly dimensional loss produced by these treatments cannot be tolerated, then cleaning in an 18 per cent (W/V) solution of chromic anhydride for two to ten minutes at 70°C.–100°C. is a suitable alternative. This pickling treatment is followed by an 'activating' dip in the following mixture for twenty minutes at 21°C.–32°C.

Phosphoric acid (85% H_3PO_4)	200 mils./litre
Sodium (or K or NH_4) bifluoride ($NaHF_2$)	100 gms./litre

The next step is the most important and involves the production of a very thin zinc immersion deposit on the surface. An alkaline solution of the following nominal composition has been found the most suitable.

Zinc sulphate monohydrate	($ZnSO_4 . H_2O$)	45 gms./litre
Tetrasodium pyrophosphate	($Na_4P_2O_7$)	210 gms./litre
Sodium fluoride	(NaF)	5 gms./litre
Sodium carbonate	(Na_2CO_3)	5 gms./litre

About five minutes' immersion at 80°C.–85°C.

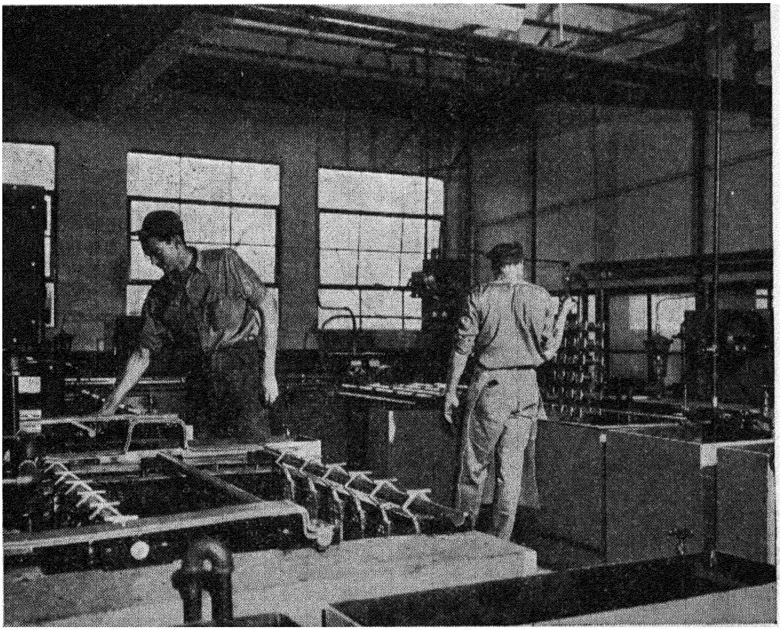


Fig. 43. Installation for nickel-chromium plating of magnesium die-castings. (*Dow Chemical Co.*)

The time of immersion will range between three and ten minutes depending on the alloy, and should be just long enough to form a thin continuous zinc coating. After this coating has been produced, a water rinse follows and then copper plating, to a thickness of 0·0003 in., in a Rochelle-cyanide bath with a pH of around 12·5. Nickel plating follows the copper flash, and a Watts-type bath is suitable. The following bath can be used where there is a possibility of an inadequate copper flash:

Nickel sulphate ($Ni_2SO_4.6H_2O$)	60 gms./litre
Boric acid (H_3BO_3)	35 gms./litre
Ammonium fluoride or bifluoride	50 gms./litre
Wetting agent	0·5 gms./litre
Hydrofluoric acid	When required to give pH 5·5
Operating temperature	46°C.–52°C.
Current density	5–15 amps./sq. ft.

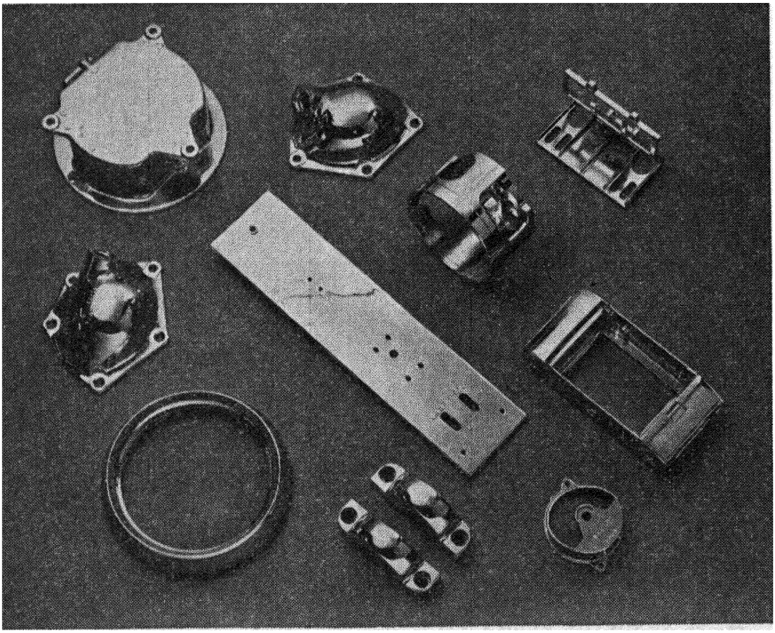


Fig. 44. Example of plated die-castings. (*Dow Chemical Co.*)

The thickness of nickel determines the degree of protection given by plating, and whilst for moderate indoor conditions 0·0005 in. thickness is appropriate, for outdoor conditions 0·0012 in. is recommended in mild environments and 0·002 in. for severely corrosive conditions. A final chromium flash of conventional type is the normal final plating stage.

The fact that this method works reasonably satisfactorily gives an indication of the basic principles to be observed in developing a method of plating on magnesium. It seems probable that alternative solutions may be developed in due course but these are still likely to be based on the essential stage of producing a zinc film on the magnesium surface. Obviously the possibility of producing plated finishes on magnesium castings will help to widen their sales appeal and fields of application.

REFERENCES

[1] J. D. HANAWALT, C. E. NELSON and J. A. PELOUBET. *Trans. A.I.M.E.* (1941), **147**, 273.

[2] L. F. LE BROCQ (contribution to discussion on paper 1011). *J. Inst. Metals* (1946), **72**, 446.

[3] *Magnesium Review and Abstracts* (1948), **8**, (i), 38.

[4] British Patent 548,479.

[5] R. G. GILLESPIE. *Materials and Methods* (1953), (11), 104–5.

[6] H. K. DELONG. *Trans. Inst. Metal Finishing* (1953), **29**.

[7] British Patent 721,445.

[8] W. F. HIGGINS, *Metallurgia* (1955), **52**, (311), 121–4.

[9] U.S. Patent 2,728,720.

[10] W. MCNEIL, *Product Finishing* (1956), **9**, (6), 46–51.

CHAPTER 11

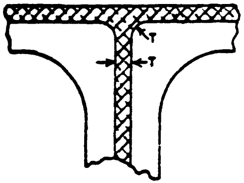
Applications of Magnesium Castings

IT HAS BECOME COMMONPLACE to stress the importance of collaboration between founder and customer at the design stage and to meet foundrymen who complain that many of their difficulties could have been reduced if they had been consulted before the component details were finalized. Whilst this section makes no claim to be a treatise on design of magnesium castings it is hoped that it will provide for the practical man suggestions which will help him to indicate possible modifications in the design to assist in obtaining sound and consistent castings economically. Obviously the best way of doing this is not merely by sketches but also in providing photographs of finished components which not only illustrate these principles but provide a broad picture of the widening field of applications for magnesium alloys.

Design Characteristics

Magnesium is the lightest of the structural metals and has the highest strength to weight ratio; even aluminium is 50 per cent heavier. The value of the modulus of elasticity (E) is low, namely $6{\cdot}5 \times 10^6$ lb./sq. in., and this value is virtually the same for all alloys. This in turn means that magnesium alloys are less rigid than other metals under certain conditions, but intelligent designing can often overcome this and still provide a saving in weight over any other alternative material. Broadly speaking this stiffening can be provided either by increasing the depth of the flange, providing webs or beading the edges of the flange, and some measure of thickening of highly stressed sections.

Fig. 45. Examples of section junctions and embossing in magnesium castings. (From 'Designing with Magnesium' (1947) p. 50. *American Magnesium Corporation.*)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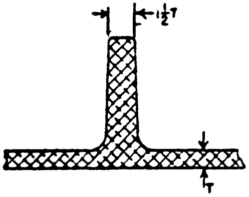
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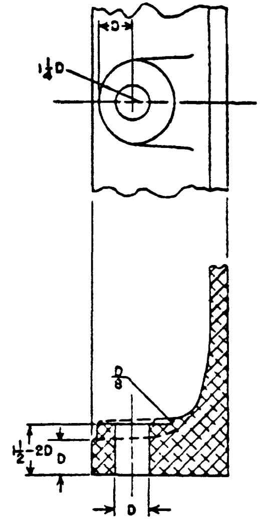
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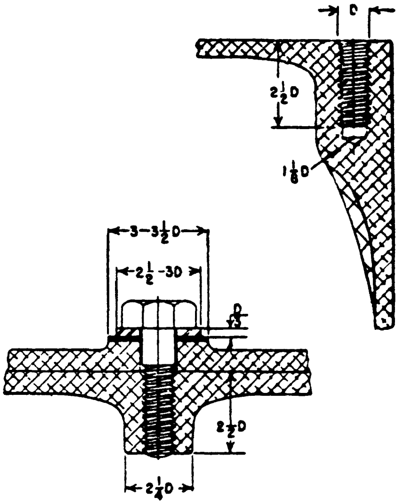
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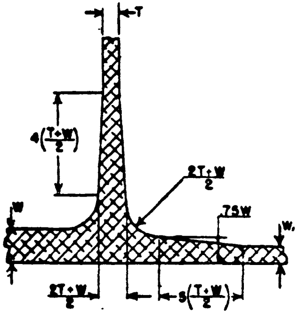
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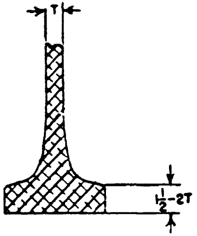
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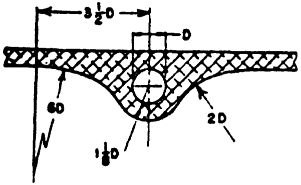
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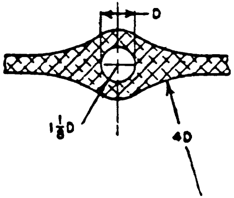
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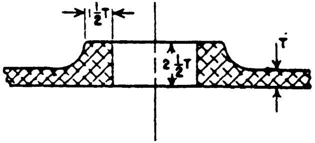
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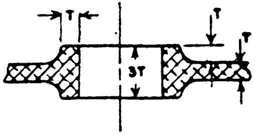
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At the same time the design must provide for careful blending of sections both to avoid stress concentrations and generally assist in feeding them. Some examples of the application of these principles are shown in *Fig.* 45. Where bosses are present near to a wall care will have to be taken in machining to see that the cutter is radiused on the edge and is not taken in so as to undercut to wall. Where threaded bolts are to be inserted in a wall the minimum depth of engagement should be around 2½ diameters when fluctuating loads are involved and rather less for ordinary tensile loading.

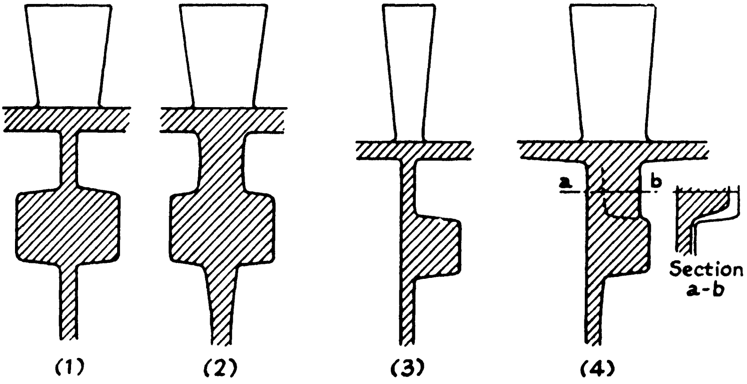

Fig. 46. Methods for feeding isolated thick bosses:

(1) and (3) are unsatisfactory, since the thin section over the boss prevents feeding from the riser. (2) and (4) recommended since by thickening the section over the boss and blending in, good feeding can be provided.

(From "Le Magnesium et Ses Alliages" (1949)—p. 33. *Société General du Magnesium*)

The design and positioning of bosses calls for care both to ensure that they will prove effective and will not fail in fatigue, and to see that they can be adequately fed. Internal bosses, where direct feeding is not always practicable, are a particular problem. Reference to *Fig.* 46 will illustrate two examples of design modifications which assist the founder. Example (1) shows a conventional design where the wall thickness is sufficiently small to prevent proper feeding. A satisfactory solution is along the lines indicated by example (2) where the wall between the outer surface and the boss has been thickened and then the section tapers away into the main web.

A similar problem is shown in the third illustration where the boss is only on one side of the web. Blending of the section in the manner shown in (4) is the usual preferred design. This principle can be also applied in the case of a boss forming the end of a component as in *Fig.* 47. Here again the unsatisfactory design is shown as example (1) whilst in (2) appropriate blending of the sections has been provided.

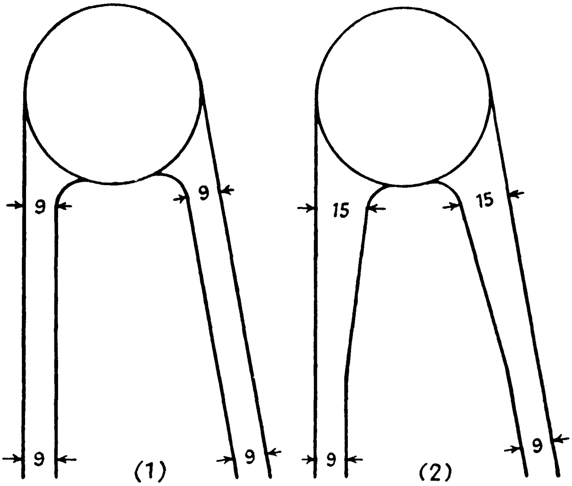

Fig. 47. Design of webs with end boss showing (1) traditional design which leads to shrinkage problems in casting and (2) preferred design.

Tolerances for Castings

Other information which the designer will require, and which can be used as a yardstick of comparison for the new founder, is the tolerances obtainable on castings, the taper required on cored holes, draft etc. Broadly speaking the tolerances obtainable are comparable with those prevailing for aluminium, although for pressure die-casting some founders claim better figures. Whilst it is not easy to give data on sand castings the following information from *A Handbook on Die Castings* by F. P. Penny (reproduced by permission of the Comptroller, Her Majesty's Stationery Office) gives general guidance on tolerances for gravity and pressure die-castings.

TABLE 15

Optimum and Minimum Recommended Wall Thickness

	Gravity	Pressure
Minimum Wall Thickness—		
Large Castings	0·187 in.	0·090 in.
Small Castings	0·12 in.	0·040°
Optimum Wall Thickness—		
Large Castings	not less than	0·187
Small Castings	minimum	0·125

TABLE 16

Limiting Length of Blind Cored Holes

	Diameter of hole in inches				
	$\frac{1}{16}$–$\frac{1}{8}$	$\frac{1}{8}$–$\frac{3}{16}$	$\frac{3}{16}$–$\frac{1}{4}$	$\frac{1}{4}$–$\frac{3}{8}$	Over $\frac{3}{8}$
Gravity die-cast	—	1½D	2D	3D	5D
Pressure die-cast	2D	2½D	3D	5D	5D

(D = actual diameter of hole)

Note: For through holes where the core can be supported in the die at both ends the length given above can be somewhat exceeded.

TABLE 17

Minimum Recommended Draft or Taper

	Up to $\frac{3}{8}$ in.	$\frac{3}{8}$ in.–1 in.	Over 1 in.
Gravity die-cast	2° 0·035 in.	3° 0·052 in.	3° 0·052 in.
Pressure die-cast	1° 0·017 in.	1½° 0·026 in.	2° 0·035 in.

Note: The taper is expressed as an included angle or as a tolerance per in. In special cases smaller drafts may be possible but for overall ease of production a larger draft than the above is preferable.

TABLE 18

Tolerances Required by Various Features

Feature	Gravity Die-Castings	Pressure Die-Castings
(*a*) On diameters, lengths and simple profiles formed wholly in one portion of a die	± ·005 in. up to 1 in. plus ± ·003 in. per in. above 1 in.	± ·0015 in. up to ¾ in. plus ± ·0015 in. per in. over ¾ in.
(*b*) Additional tolerance to allow for imperfect closing of the die	± ·012 in.	± ·004 in.
(*c*)* Positional tolerances required by features formed wholly within one die block	·003 in. up to 1½ in. and ·0015 in. per in. above 1½ in.	·001 in. up to 1½ in. and ·0015 in. per in. over 1½ in.
(*d*)* Allowance for imperfect lateral location when impression is formed in more than one die block or piece	0·010 in.	·003 in.
(*e*) Additional tolerance to allow for imperfect location of a movable core	·002 in.	0·005 in.

*Tolerances refer to maximum metal conditions (vide B.S. 308: 1953 Section on Dimensioning and Tolerancing).

These figures are on the whole a little conservative, most especially in terms of minimum taper and maximum depth of cored hole. Thus, Schneider and Barnickel* give the following comparative data (Table 19) for minimum cored hole sizes and maximum hole depth for magnesium, aluminium and zinc pressure die-castings.

**Metall.* (1950), 4, (11-12), 225–228.

TABLE 19

Comparative Data for Cored Holes in Pressure Die-Castings in Various Metals

	Mg	Al	Zn
Minimum Cored Hole Dia. in mm.	1·5	2·5	1·0
Maximum Hole Depth			
Blind Holes	3 × ⌀	3 × ⌀	4 × ⌀
Through Holes	6 × ⌀	5 × ⌀	6 × ⌀

where ⌀ = hole diameter

It is also claimed that if metal is solidifying around a cored out boss where the cores are 10–20 mm. in length and the boss is at least 5 mm. thickness only 0·3–0·6 per cent taper is required for magnesium alloys as against 0·6–1 per cent for aluminium. The obvious tendency for the less experienced founder will be to err on the side of safety.

Prevention of Galvanic Corrosion

Inserts of other metals are sometimes used in magnesium castings either to provide local wear resistance or occasionally to provide a means of attachment for other components. However, since in conditions where an electrolyte (moisture) can collect at the junction between the magnesium casting and the insert there is a strong possibility of galvanic corrosion unless suitable precautions are taken. Where steel is used cadmium or zinc plating will give fairly good protection against such corrosion but a minimum thickness of 0·0005 in. for cadmium and 0·001 in. for zinc respectively are recommended. This will normally be applied to inserts before casting. An example of a cast in piece is shown in *Fig.* 49(a).

Where bolts are used for fastening two magnesium components not only should the bolts be plated but a washer placed under the head to prevent indentation of the casting, and separated from the casting by an insulating non-metallic washer (see *Fig.* 49(b)). Where fastened to a dissimilar metal a similar insulating layer should be inserted at the mating faces (*Fig.* 48(c)). All faying surfaces should be protected by a zinc chromate jointing compound.

In general contact with copper base alloys should be avoided, although cadmium plated or tinned copper has sometimes been used satisfactorily. The aluminium alloys containing copper are also not particularly satisfactory in contact with magnesium and some protection such as anodizing is recommended. The aluminium alloys containing magnesium as the principal alloying element are satisfactory if conditions are mild although even with aluminium alloys steps may have to be taken to insulate them from the magnesium components in the more corrosive environments. Whilst the danger of galvanic corrosion is often over emphasized it is necessary to be acquainted with it and the remedies which can be applied.

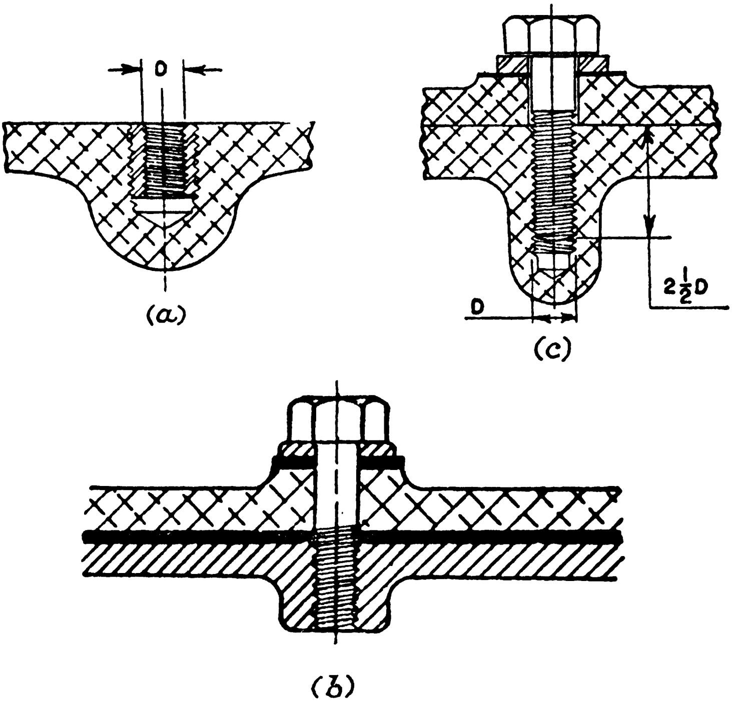

Fig. 48. Methods of avoiding galvanic corrosion at bimetallic junctions showing (*a*) cast in cadmium plated insert (*b*) insulation under steel bolt head (*c*) insulating layer between magnesium casting and other metal.

The Development of Magnesium Casting Applications

Magnesium is the lightest of the common metals and it is abundant; extraction from sea water has proved itself to be economic and the available magnesium from this source alone is more than adequate for any foreseeable period even with a large increase in its consumption. Further, there are large quantities of good quality rocks, such as dolomite, which also provide an economic source for extraction of the metal. The strategic aspect of this question is not a matter to be discussed in the confines of this account, but in passing it should be noted that it is the only common metal in which Britain is, and can continue to be self-sufficient.

To some extent the growth of the magnesium industry has been overshadowed by, and possibly hampered by, the momentous development of the aluminium industry which was established some years earlier. In some respects magnesium is complementary to aluminium, but in applications where lightness is a major factor, price will continue to be the criterion deciding which of the metals shall be used. On the other hand price is not a mere question of price per pound but really involves a careful assessment of the over-all cost of producing a component including many indirect charges. Magnesium castings are more easily machined and higher speeds are possible, than for most of the aluminium alloys particularly those containing silicon as a major alloying element. However, this free machining quality can only be fully exploited if machines and techniques are employed which can utilize these qualities.

For some years a major outlet for magnesium alloy castings has been the aircraft industry where weight reduction is at a premium and the higher initial cost has not been a deterrent, since either the higher performance of a military aircraft or greater payload for the civilian airline may in fact mean that magnesium castings are economic in the broadest sense of the term. Magnesium is also finding applications in other fields where saving in weight, and hence reduction in inertia are important. Whilst magnesium is two-thirds the weight of aluminium conversion of a magnesium component to aluminium actually involves an increase of 50 per cent in weight of the assembly which can be very significant in terms of power consumption in machinery.

The jet engine has stimulated enormously the development of magnesium alloys particularly for castings, and it would be difficult to list the components now produced as *Fig.* 49 castings. Sufficient indication can be given in mentioning their use for air-intake casings, diffuser assemblies, gear drive housings, air brakes, landing wheels and airborne radar reflectors. Some of these castings, such as the ones illustrated, are examples of a high standard of foundry craftmanship whilst their standard of soundness is testimony of a high level of metallurgical control. (*Fig.* 50)

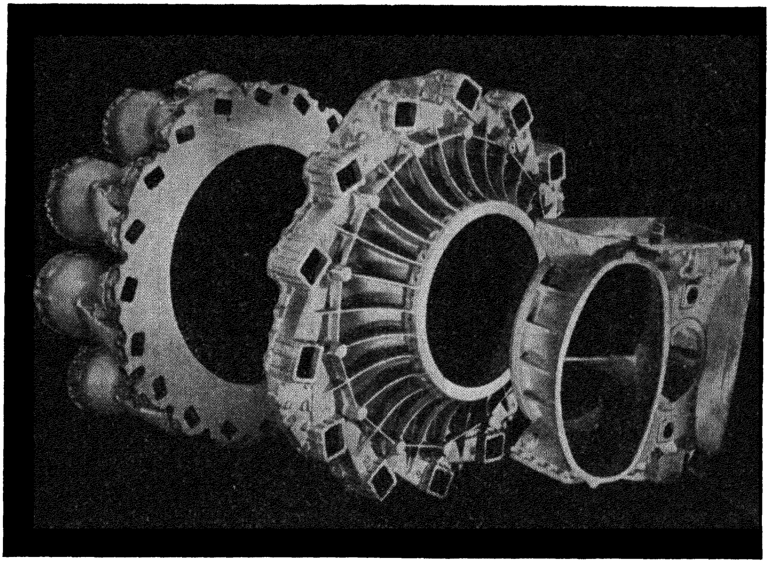

Fig. 49. DTD 708 castings for the De Havilland 'Ghost' jet propulsion unit. Castings by Sterling Metals Ltd.
(*De Havilland Aircraft Co. Ltd.*

However, valuable as the aircraft experience has been, it is evident that in the long run the wider use of magnesium in civilian industries is vital for the economic stability and long-term expansion of the industry. The properties of magnesium should ensure their more widespread use once they are known and appreciated by engineers, designers and operatives. Already a sound basis has been laid in many fields and it should be helpful to the founder to have recorded in the next few pages some examples of successful applications of the metal.

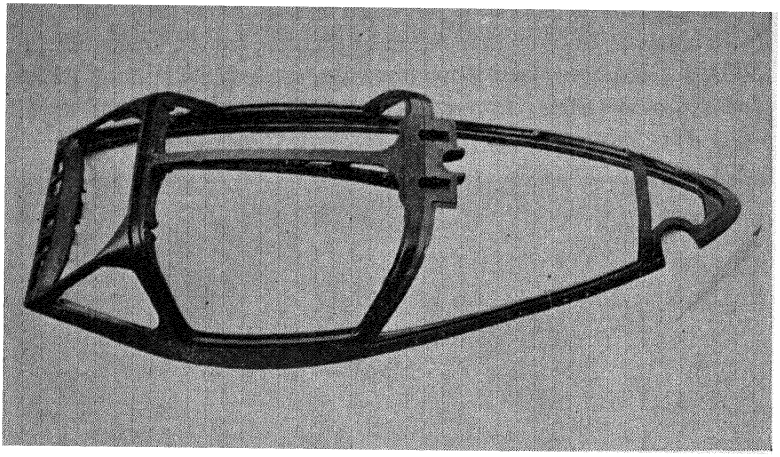

Fig. 50. Assembly of De Havilland 'Sea Venom' canopy castings in DTD 748 alloy, 8 ft. 6 in. by 1 ft. 8 in. Withstands jettisoning under 10 ft. of water.
(*De Havilland Aircraft Co. Ltd.* Photo: *J. Stone & Co. (Charlton) Ltd.*)

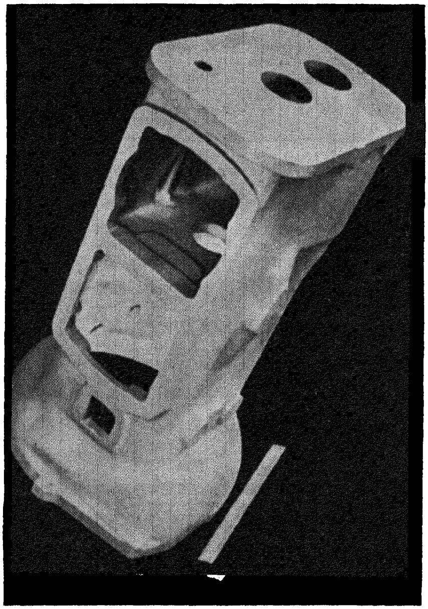

Fig. 51. Transmission case of Ferguson tractor (unmachined weight 54 lb.) in a commercial alloy.
(*H. Ferguson Ltd. Casting by Sterling Metals Ltd.*)

Civilian Application

In Great Britain one of the outstanding examples of the post-war commercial use of magnesium alloy castings has been components such as the transmission case (*Fig.* 51) and lower housing of the Ferguson tractor engine. Over 250,000 of these have been made and they have been sold to all parts of the world without complaint of failure from corrosion or material defects. In this application a commercial magnesium-alluminium alloy made from remelted scrap was used. One of its principal advantages was that the high machining speeds employed enabled components to compete in cost with other metals.

This application was built on experience gained over a number of years with the use of similar castings including valve covers, engine rear support and gearboxes used for a standard commercial engine produced by Associated Equipment Co. More recently, in Germany, engine castings in a secondary magnesium alloy have been used on production models of a mass production car and there are indications that they are beginning to be employed in other engines.

Another important post-war application has been in the textile industry where pressure die-cast ends for bobbins have become established, and also gravity die-cast ends to warp beams; these are sometimes used in conjunction with magnesium alloy tubes although aluminium alloy has often been favoured. Cast backing drums for beaming machines have also been made and these may be as large as 2 ft. in diameter and 4 ft.–5 ft. in length. (*Fig.* 52.) At the other end of the scale small die-cast weavers' pirns weighing only an ounce or two are in use.

In the field of light-weight tools and equipment much progress has been made. In Germany prior to 1939 about 70 per cent of the portable tool castings were magnesium pressure die-castings. In this country and the U.S.A. several manufacturers have changed to the same material for portable power-driven chain saws, air-powered hand tools, sanders etc. Broadly speaking it has been in the heavier tools that magnesium has been most successful since the lower weight on the small tools has not adequately compensated for higher material costs.

Optical and precision instruments have provided another expanding outlet. Pressure die-cast binocular casings and camera parts have been used satisfactorily by several manufacturers, and auxiliary equipment such as enlarger components have also come into use.

One well-known television camera (*Fig.* 53), consists of an assembly of die-castings and pressings in a magnesium-aluminium alloy which house the electrical and optical gear. Small 16 mm. film projector components have been in production for one U.S. manufacturer since the end of the war.

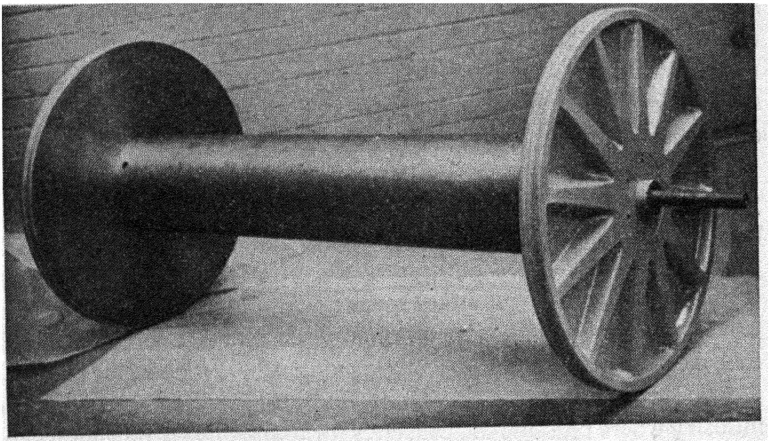

Fig. 52. Magnesium high-speed warping beam with 30-in. dia. flange and 10 in. dia. barrel. (*Magnesium Electron Ltd.*)

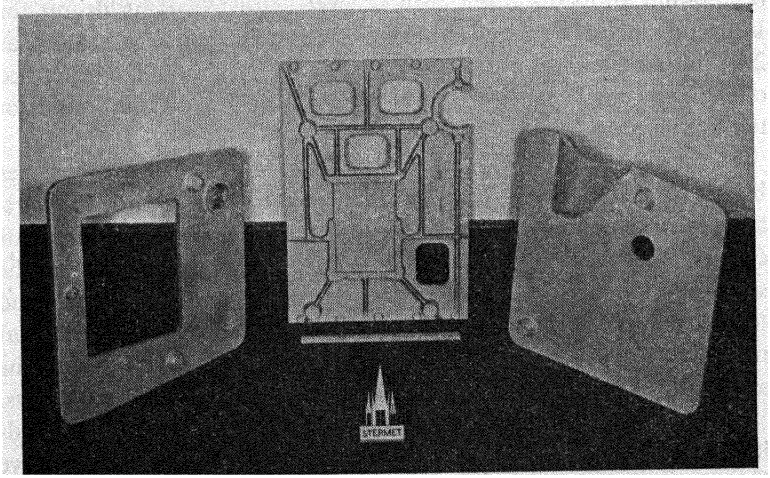

Fig. 53. Cover plates in commercial alloy for the Pye Photicon T.V. Camera. (*Messrs Pye Ltd. Castings by Sterling Metals Ltd.*)

Mechanical handling has provided several interesting uses for magnesium alloys. Of these the one most familiar to some foundries will be magnesium core plates, moulding boxes (*Fig.* 54) and bottom boards which have found acceptance in many quarters. Gravity die-cast cable drums have also been found to compete successfully with their wooden counterparts for winding of cables whilst allied to this are wire spools and reels in the same metal. Pulley blocks' tackle parts have also used this light metal instead of cast iron with obvious advantages in ease of handling and erection.

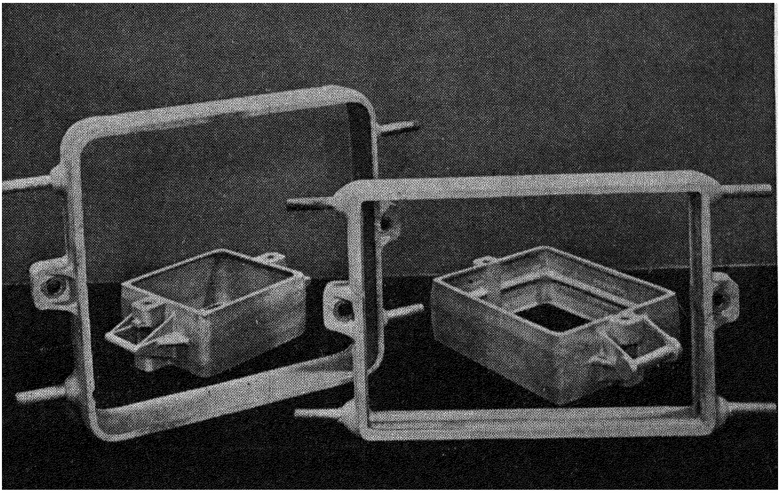

Fig. 54. Moulding boxes in magnesium alloy.
(*J. Stone & Co.* (*Charlton*) *Ltd.*)

Allied to this there are a number of interesting applications in the field of building materials production and contractors' equipment. One of these is the use of die-cast pallet in the production of roofing tiles and allied to it the use of large castings for concrete forms and shuttering. The alkali resistance of magnesium appears to permit a 'cleaner finish' than is possible with aluminium. Die-cast brick hods have been made, also plasterer's tools and brick handling tongs—(*Fig.* 55) these latter being of Canadian or American manufacture. The handles of large pipe wrenches have also been made in magnesium alloy.

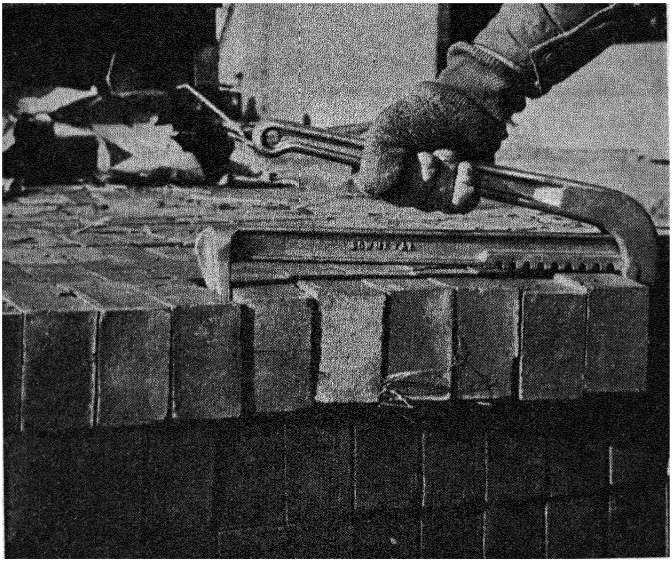

Fig. 55. Brick-handling tongs made from two gravity die-castings.
(*Dow Chemical Co. Ltd.*)

Office machinery also accounts for a proportion of the output of die-castings. Several typewriter manufacturers have used them for frames and casing parts, and miscellaneous components in frames of electric typewriters, calculators, dictaphones and similar equipment represent allied applications. (*Fig.* 56.)

In the automobile field there are still great possibilities for magnesium. Although there are several established applications in the commercial vehicle trade the motor car has provided negligible outlets for castings in the metal as far as Great Britain is concerned. From the United States it is reported that rapid progress is being made. Several million clutch pistons forming part of an automatic transmission system are said to have been used, whilst many thousand die-cast clutch housings have recently gone into service. Decorative parts such as steering column shrouds, brackets, instrument parts, etc., are stated to have been in production for several years.

Pre-war experience in Germany where magnesium was forced upon manufacturers because of shortage of the more conventional metals provides some interesting experiences. Of course there were failures particularly from poor design where the change was made to magnesium without taking into account its particular properties and modifying the detailed design accordingly. Not surprisingly some troubles were experienced with galvanic corrosion although far less than might have been feared. However, the general experience is an encouraging one and has been confirmed by British and American experience.

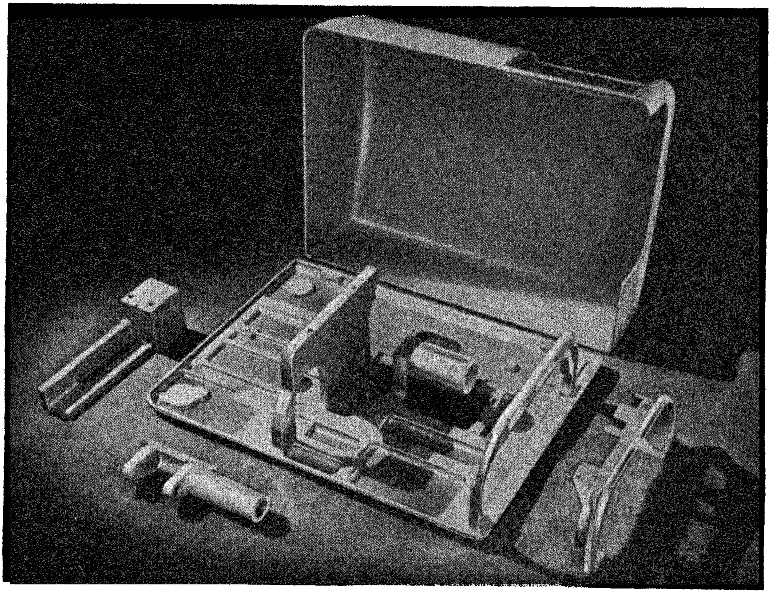

Fig. 56. Set of magnesium alloy die-castings for portable dictaphone machine. (*J. Stone & Co.* (*Charlton*) *Ltd.*)

We can see therefore that whilst the range of applications is still somewhat limited it extends over a very wide range of industries and provides inspiration to those who believe that the magnesium founding industry is still only just out of its infancy. Given an understanding of the characteristics of the metal, an appreciation of its limitations an energetic desire to see it used where it is appropriate, and maintaining the faith in the metal which inspired its pioneers, there is no reason why it should not develop healthily to maturity.

This then brings us to the conclusion of our account in which we have attempted to show that magnesium casting technology is based on common-sense principles that can be determined from the chemical and physical properties of the metal. In many ways it is an account that brings together the positive achievements of the industry. Yet behind all this there is a story; that of early pioneers who despite their setbacks and disappointments maintained their faith in the metal. Some of them triumphed over these difficulties, others failed or did not live to see success.

Contributions have been made to magnesium technology by men of every major industrial nation, but in the last resort the strength of the team of people who produced magnesium in its various forms has been based on the ordinary operative who can in the last resort determine the success or otherwise of any technique.

Classified Bibliography

The references listed below are a selection from the published literature of papers concerning various aspects of magnesium alloys and their technology. They are classified under headings which roughly correspond to the main chapters of the book but a heading 'Corrosion' has been included to provide a summary of the principal published papers which are concerned with this field. Since corrosion is a somewhat specialized subject the foundryman may get more assistance from the service experiences quoted under the heading 'Design and Applications'. Where there is any doubt about the suitability of a magnesium alloy for particular applications guidance from a suitable authority should be sought. These references are not a complete list of published papers but are designed to help where further reading may help to prevent undue repetition of work or give the reader a background of the research and development work already undertaken.

Properties of Alloys

[1] G. Siebel. Technical Magnesium Alloys and Magnesium containing Aluminium Alloys; Research and Development by I. G. Farben, 1920–45. *Z. Metallkunde* (1952), **43**, (7), 238–44.

[2] A. J. Murphy and R. J. M. Payne. Magnesium-Cerium-Zirconium Alloys—Properties at Elevated Temperatures. *J. Inst. Metals* (1947), **73**, 105–27.

[3] G. A. Mellor and R. W. Ridley. The Creep Strength of some Magnesium Alloys containing Cerium. *J. Inst. Metals* (1948–9), **75**, 679–92.

[4] T. E. Leontis. The Properties of Sand Cast Magnesium-Rare Earth Alloys. *Trans. A.I.M.E.* (1949), **185**, 968–86.

[5] K. Grube and L. W. Eastwood. Magnesium-Cerium Cast Alloys for Elevated Temperature Service. *Proc. A.S.T.M.* (1950), **50**, 989–1012.

[6] J. Navarro-Alcacer. *The Tensile Strength of Cast Magnesium Alloys.* Neue Giesseri (Tech.-Wiss Beichefte) (1950), (3), 115–17.

[7] G. Siebel and H. Vosküller. The Technical Properties of Magnesium-Cerium-Zinc Alloys. *Metall.* (1950), **4**, (17/18), 370–4.

[8] C. F. Hildebrand and F. P. Streiter. Mechanical Properties of Sand Cast Magnesium-Zinc-Zirconium Alloys. *Trans. Amer. Found. Soc.* (1952), **60**, 595–600.

[9] R. Pradeau. The Mechanical Properties of Magnesium-Zirconium Alloys Z5Z and RZ5. *Proc. International Foundry Congress* (1953).

[10] C. P. J. Ball, A. C. Jessup, P. A. Fisher and J. B. Wilson. Further Progress in the Development of Magnesium-Zirconium Alloys. *Trans. A.I.M.E.* (1953), **197**, 924–31.

[11] J. Gris. The Influence of Added Elements on the Elevated Temperature Properties of Magnesium Alloys. *Metaux, Corrosion-Ind.* (1952), **27**, (327), 458–62; (1953), **28**, (330), 87.

[12] J. W. Meier and M. W. Mortensen. Development of High Strength Magnesium Casting Alloy ZK61. *Trans. Amer. Found. Soc.* (1950), **58**, 742–50.

[13] T. E. Leontis. Properties of Magnesium-Thorium and Magnesium-Thorium-Cerium Alloys. *Trans. A.I.M.E.* (1952), **194**, 287–94.

[14] T. E. Leontis. Effect of Zirconium on Magnesium-Thorium and Magnesium-Thorium-Cerium Alloys. *Trans. A.I.M.E.* (1952), **194**, 632–44.

[15] K. E. Nelson. The Properties of Sand Cast Magnesium-Thorium-Zinc-Zirconium Alloys. *J. Metals* (1953), **5**, (11), 1493–7.

Melting and Alloying

[1] C. E. Nelson. Melting and Refining Practice for Magnesium. Symposium on Non-Ferrous Melting Practice. *A.I.M.E.* (1946), p. 79–92.

[2] E. F. Emley. Non Metallic Inclusions in Magnesium Base Alloys and the Flux Refining Process. *J. Inst. Metals* (1948–9), **75**, 431–80.

[3] R. G. Wilkinson and S. B. Hirst. The Control of Quality in the Melting and Casting of Magnesium Alloys. *J. Inst. Metals* (1952–3), **81**, 594–6.
Magnesium Base Alloys. *J. Inst. Metals* (1945), **71**, **1–22.**

[4] F. A. Fox and E. Lardner. *An Exploration of the Problem of Superheating.*

[5] C. H. Mahoney, A. L. Tarr and P. E. LeGrand. A Study of Factors Influencing Grain Size in Magnesium Alloys and a Carbon Inoculation Method for Grain Refinement. *Trans. A.I.M.E.* (1945), **61**, 328–47.

[6] J. A. Davis, L. W. Eastwood and J. De Haven. Grain Refinement of Magnesium Casting Alloys. *Trans. Amer. Found. Soc.* (1945), **53**, 352–60.

[7] W. A. Baker, M. D. Eborall and A. Cibula. Influence of Primary Particles on the Grain Size of Cast Magnesium-Aluminium Alloys. *J. Inst. Metals* (1952–3), **81**, 43–48.

[8] K. S. Sealander. Melting Practice for Magnesium Alloys. *Foundry* (1951), **79**, (5), 94–95 and 204–7.

[9] W. Mannchen. Experiments on the Influence of Calcium and Hydrogen on the Grain Size of (Chill Cast) Magnesium and Magnesium Alloys. *Z. Metallkunde* (1950), **41**, (8), 240–3.

[10] A. Kiel. Spectrochemical Investigation of the Effect of Beryllium on the Inflammability Hazard of Molten Magnesium Alloys. *Z. Metallkunde* (1951), **42**, (1), 13–16.

[11] F. Sauerwald. The Solubility and Behaviour of Hydrogen in Liquid and Solid Magnesium Alloys. *Z. Anorg. Chem.* (1949), **258**, (1/2), 27–32.

[12] W. A. Baker. Microporosity in Magnesium Alloy Castings. *J. Inst. Metals* (1945), **71**, 165–204.

[13] F. A. Fox. The Properties of Some Magnesium-Aluminium-Zinc Casting Alloys and the Incidence of Microporosity. *J. Inst. Metals* (1945), **71**, 415–39.

[14] E. J. Whittenberger and F. N. Rhines. Origin of Porosity in Castings of Magnesium-Aluminium and Other Alloys. *Trans. A.I.M.E.* (1952), **194**, 409–20.

[15] V. M. Sharov, B. S. Morozov and V. M. Pletinev. Gas Porosity in Magnesium Alloy Castings. *Liteinoe Proizvodstvo* (1952), **6**, 16–19.

[16] M. Bardot. Study of Microporosity in Casting of Magnesium Alloys. *Fonderie* (1954), **94**, 3687–92.

[17] W. P. Saunders and F. P. Streiter. Alloying Zirconium to Magnesium. *Trans. Amer. Found. Soc.* (1952), **60**, 581–90.

[18] F. P. Streiter. Magnesium Casting Alloys containing Zirconium. *Metal Progress* (1953), **63**, (3), 75–82.

[19] E. F. Emley. Non-Metallic Inclusions in Magnesium Base Alloys containing Zirconium. *J. Inst. Metals* (1948–9), **75**, 481–512.

[20] J. Gris. Seeking for Grain Fineness in Magnesium Alloys. *Proc. Cong. Intern. Fonderie* (Bruxelles), (1951), 97–104.

[21] H. G. Warrington. Some Characteristics of Magnesium Alloys containing Thorium. *Light Metals* (1954), **17**, (194), 146–7. (Paper presented at 9th Annual Meeting of the Magnesium Association—New York 1953.)

[22] C. E. Nelson. Magnesium Sand Casting Alloys containing Thorium. *Trans. Amer. Found. Soc.* (1953), **61**, 315–326.

[23] K. E. Mann. Ein Beitrag über die Wirkung kleinster Berylliumgehalte, Magnesiumlegierungen. Z. Metallkunde (1946), **46**, (1), 12–24.

[24] E. F. Emley. The Refining of Magnesium. Institution of Mining and Metallurgy. Symposium on the Refining of Non-Ferrous Metals (1950).

[25] W. Zachintzach. A Coreless Mains-Frequency Crucible Induction Furnace for Magnesium Alloys. *Giesserei* (1952), **39**, (16), 381–7.

[26] Dow Chemical Co. Open Pot Melting for Magnesium. *Bulletin* DM26d (1954), 6 pp.

[27] Dow Chemical Co. Crucible Melting of Magnesium. *Bulletin* DM27d (1954), 14 pp.

[28] Organization for European Economic Co-operation. 'Magnesium Fabricating and Casting.' *Technical Assistance Mission* No. 104 (1956), 86 pp.

Production of Sand Castings

[1] L. W. Eastwood. Selecting Inhibitors for Magnesium Moulding Sands. *Foundry* (1944), **72**, (12), 82–83, 232, 234; 1945, **73** (1), **80–81**, 208, 210.

[2] W. C. Newhaus. Magnesium Sand Foundry Technology. *Foundry* (1953), **81**, (5), 147–9.

[3] Anon. Shell Moulds for Magnesium Castings. *Machinery* (London) (1953), **83**, (2141), 1069–70.

[4] G. B. Partridge. Technical Control in a Magnesium Foundry. *Foundry Trade Journal* (1946), **79**, (1550), 5–8.

[5] M. W. Martinson and J. W. Meier. Magnesium Foundry Practice in Canada. *Canadian Metals* (1950), **13**, (8), 10–13, 40–42, 50.

[6] T. E. Leontis and H. E. Elliott. Magnesium Castings. *Foundry* (1953), **81**, **(5)**, 147–9.

[7] A. Cristello. Gating, Risering and Chilling of Magnesium Castings. *Amer. Foundryman* (1947), **7**, (4), 7–10.

[8] H. E. Elliott and J. G. Mezoff. Effect of Gating Design and Metal Flow Conditions in the Casting of Magnesium Alloys. *Trans. Amer. Soc.* (1948), **56**, 223–44.

[9] J. G. Mezoff and H. E. Elliott. A Study of Factors Affecting the Pouring Rates of (Magnesium Alloy) Castings. *Trans. Amer. Found. Soc.* (1948), **56**, 279–84.

[10] H. E. Elliott. Gating and Risering of Magnesium Castings. *Amer. Foundryman* (1954), **25**, (4), 56–62; (5), 113–22.

[11] G. B. Partridge. Founding Magnesium-Zirconium Alloys. *Met. Ind.* (London) (1953), **83**, (5), 83–85.

[12] K. E. Nelson and F. P. Streiter. Casting of Magnesium-Rare-Earth-Zirconium Alloys in Sand Moulds. *Trans. Amer. Found. Soc.* (1950), **58**, 400–7.
Several Magnesium-Rare-Earth Sand Casting Alloys. *Trans. Amer. Found.*

[13] K. E. Nelson and F. P. Streiter. A Castability and Property Comparison of Several Magnesium-Rare-Earth Sand Casting Alloys. *Trans Amer. Found. Soc.* (1951), **59**, 532–43.

[14] R. J. M. Payne. Inverse Segregation in Cast Magnesium Alloys. *J. Inst. Metals* (1947), **72,** 565–81.

[15] H. M. Skelly and D. C. Sunnucks. *Segregation in Magnesium-Rare-Earth-Zinc-Zirconium Alloys.* A.F.A. Preprint No. 54.—23.

[16] N. Sheptak. Casting Magnesium in Shell Moulds. *Trans. A.F.S.* (1953), **61,** 157–62.

[17] K. E. Nelson. Magnesium Sand Casting Alloys Containing Thorium. *Trans. Amer. Found. Soc.* (1953), **61,** 315–26.

[18] H. E. Elliott. Casting High Quality Magnesium. *Modern Castings* (1955), **28,** (1), 38–45.

[19] K. E. Nelson. Foundry Characteristics and Properties of Magnesium Sand Casting Alloy HZ32A. *Trans Amer. Found. Soc.* (1955), **63,** 591–606.

[20] N. Sheptak. Tensile Property Evaluation of Shell Mold Cast versus Green Sand Cast Magnesium Alloy Test Bars. *Trans. Amer. Found. Soc.* (1955), **63,** 157–62.

[21] K. E. Nelson and W. P. Saunders. An Evaluation of ZH62XA Magnesium Sand Casting Alloy. *Foundry* (1956), **84,** (7), 200–2.

[22] W. E. Pearson. Effects of Section Size Variations in a Test Casting on Properties of some Magnesium-Aluminium-Zinc Alloys. *Foundry* (1956), **84,** (7), 202–4.

Gravity Die-Casting (Permanent Mould Casting)

[1] M. R. Hinchcliffe. An Outline of Gravity Die-Casting. *Proc. Inst. Brit. Foundrymen* (1943–4), **37,** B28–36.

[2] A. Sugar. Permanent Mould Castings. *Metals and Alloys* (1945), **21,** (4), 1015–25.

[3] A. Sugar. Recommended Practices for Aluminium and Magnesium Permanent Mould Castings. *Aluminium and Magnesium* (1946), **2,** (8), 12–14, 30–32 and (10), 8–9, 16–17.

[4] Jean Dupont. Chill Casting Magnesium Alloys. *Fonderie* (1947), **20,** 770–2.

[5] H. Chase. Casting Magnesium in Metal Moulds. *Iron Age* (1947), **160,** (13), 73–76.

[6] S. Guastalla. Modern Techniques of Die-Casting Aluminium and Magnesium Alloys. *Allumino* (1948), **17,** (1/2), 7–33.

[7] E. M. Cramer and B. Mohr. Magnesium Handles Cast in Permanent Moulds. *Amer. Foundryman* (1950), **17,** (16), 28–29.

[8] E. M. Gingerich, M. E. Gantz and R. T. Woods. Magnesium Alloy Permanent and Semi-Permanent Mould Castings. *Trans. Amer. Found. Soc.* (1953), **61,** 502–9.

[9] A. M. Oskin. Porosity of Permanent Mould (Magnesium) Castings. *Liteinse Proizvodsto* (U.S.S.R.) (1955), **1,** 1–3.

Pressure Die-Casting

[1] A. Grossman. Effect of Pouring and Die Temperatures on the Quality of Pressure Die-Castings. *Metallwirtschaft* (1944), **23,** (16/17), 135–42.

[2] J. L. Erickson. Pressure Die Casting Magnesium. *Light Metals* (1947), **10,** (115), 390–5.

[3] J. L. Erickson. Die Casting Inserts—Recommended Techniques for Magnesium Alloy Castings. *Metal Ind.* (London) (1947), **71,** (7), 129–30.

[4] A. C. Street. Die-Casting Progress IV—Pressure Die-Casting of Magnesium Alloys. *Metallurgia* (1948), **38,** (223), 3–5.

[5] K. Schniender and O. Barnickel. Pressure Die-Casting—Its Technical Status and Field of Application. *Metall.* (1949), **3,** (23/24), 409–13.

[6] A. Bauer. Magnesium Die-Casting in Germany. *Modern Metals* (1950), **6**, (1), 17–22; (2), 27–33 and (3), 31–35.

[7] M. Billing. The Problem of Equipment in Pressure Casting. *Fonderie* (1950), **53**, 2059–60.

[8] G. Lieby. Magnesium Alloys for Pressure Die-Castings. *Metall.* (1950), **4**, (11/12), 225–8.

[9] R. C. Cornell. Die-Casting Magnesium Alloys. *Trans. Amer. Found. Soc.* (1951), **59**, 398–400.

[10] G. F. Hodgson. Magnesium Die-Casting. *Foundry* (1954), **82**, (2), 102–5, 252–6.

[11] Dow Chemical Co. Die Casting Practice for Magnesium. *Bulletin* DM11f (1954), 13 pp.

[12] F. L. Burkett. Beryllium in Magnesium Die-Casting Alloys. *Trans. Amer. Found. Soc.* (1954), **62**, 442–4.

[13] F. C. Bennett. Hot Chamber Magnesium Die-Casting. *Light Metals* (1955), **18**, (204), 81–2; also *Modern Metals* (1954), **10**, (11), 76, 78–80.

[14] S. H. Egbert. (Pressure) Die-Casting Magnesium. *Foundry* 1956, **84**, (7), 81–9.

Heat Treatment

[1] Anon. Heat Treating Magnesium Castings without Controlled Atmospheres. *Indus. Heating* (1946), **13**, (1), 134, 136.

[2] A. G. Gray. Heat Treating and Machining Magnesium Alloys. *Steel* (1947), **120**, (5), 102–4, 106.

[3] C. B. Willmore and W. S. Peterson. The Ignition of Magnesium Alloys during Heat Treatment. *Materials and Methods* (1947), **26**, (1), 85–88.

[4] F. A. Fox and E. Lardner. An Investigation of the Effects of Precipitation of Binary Magnesium Alloys. *J. Inst. Metals* (1948), **64**, 373–96.

[5] R. E. Flanigan, D. D. Cornet, R. Hultgren, J. T. Lapsley and J. E. Dorn. Factors Involved in Heat Treating a Magnesium Alloy (AZ92). *Trans. A.I.M.E.* (1948), **175**, 524–60.

[6] T. E. Leontis and H. E. Elliott. The Ageing of Sand Cast Magnesium-Aluminium-Zinc Alloys. *Trans. A.I.M.E.* (1951), **191**, (2), 120–4.

[7] E. M. Gingerich. Heat Treatment of Magnesium Alloy Castings. *Trans. Amer. Found. Soc.* (1952), **60**, 641–8.

[8] E. Lardner. The Formation of Intra-crystalline voids in Solution Treated Magnesium Alloys. *J. Inst. Metals* (1952/3), **81**, (9), 439–42.

[9] R. J. M. Payne. Stress Relief and Allied Problems in Magnesium Castings. *J. Inst. Metals* (1950/1), **78**, 147–68.

Inspection

[1] L. R. Curtis. Fluoroscopic Inspection of Aluminium and Magnesium Castings. *Non-Destructive Testing* (1948–9), **7**, (3), 25–30; (4), 24–27.

[2] J. G. Schneeman and T. E. Piper. Fluoscopic Inspection of Light Metal Alloys. *Non-Destructive Testing* (1950/1), **9**, (3), 20–22; also *Machinery* (London.) (1951), **79**, 2039, 1025–9.

[3] J. J. Pierce. Interpretation of Radiographs of Aluminium and Magnesium Castings. *Non-Destructive Testing* (1953), **11**, (6) 27–31.

[4] F. A. Allen. A Method of Statistical Quality Control for Light Alloy Castings. *Found. Trade J.* (1945), **75**, (1481) 3–5.

[5] Anon. Fluorescent Ink as an Inspection Tool *Light Metals* (1952), **15**, (172), 234–5.

[6] R. C. McMaster. Non-Destructive Testing. *Proc. A.S.T.M.* (1952) **52**, 617–88.

Surface Treatment

[1] H. K. DELONG. Surface Finishing and Protection of Magnesium Alloys. *Modern Metals* (1949), **5**, (6), 26–29.

[2] G. C. CLOSE. Magnesium Processing and Finishing. *Products Finishing* (1950), **14**, (7), 32–34, 36, 38, 40.

[3] ANON. Finishing Magnesium—Cleaning, Pre-Treatment and Chemical Finishing Methods. *Product Finishing* (Lond.) (1951), **4**, (7), 40–51, 92.

[4] J. D. BREGMAN. Cleaning, Dow-Treating and Finishing Magnesium Products. *Industrial Finishing* (U.S.A.) (1952), **28**, (11), 20–34.

[5] L. F. LEBROCQ and H. G. COLE. The Importance of Chemical Buffering in Treatment of Magnesium Alloys. *Metaux et Corrosion* (1949), **24**, (287/8) 171–91.

[6] ANON. Barrel Finishing (of Magnesium), *Product Finishing* (Lond.) (1952), **5**, (6), 52–56.

[7] G. BLACK. Electrolytic Polishing of Magnesium. *Metal Finishing* (1947), **45**, (6), 86–87, 94; (7), 84–86.

[8] A. G. GRAY, Organic Finishing of Magnesium, *Products Finishing* (1949), **13**, (4), 72–76.

[9] H. A. BARBARIAN. Finishing Systems for Magnesium. *Precision Metal Moulding* (1953), **11**, (12), 59–63.

[10] R. G. GILLESPIE. Properties of HAE Finish for Magnesium. *Materials and Methods* (1953), **38**, (5), 104–5.

[11] K. HUBER. Anodic Formation of Coatings on Magnesium, Zinc and Cadmium. *J. Electrochem. Soc.* (1953), **100**, (8), 376–82.

[12] P. ZYLSTRA. New Anodic Coatings. *Modern Metals* (1955), **11**, (1), 42–48.

[13] L. D. and D. J. GODDEYNE. Electroplating a Magnesium Rule Case. *Modern Metals* (1955), **10**, (12), 64–68.

Corrosion

[1] J. D. HANAWALT, C. E. NELSON and J. A. PELOUBET. Corrosion Studies of Magnesium and its Alloys. *Trans. A.I.M.E.* (1942), **147**, 273–8.

[2] F. A. FOX and C. J. BUSHROD. Further Observations on the Protective Influence of Magnesium in the Corrosion of Aluminium Containing Magnesium Alloys. *J. Inst. Metals* (1945), **71**, 255–65.

[3] F. A. FOX. Investigation on the Effect of Zinc on the Corrosion of Some Magnesium Casting Alloys. *J. Inst. Metals* (1947), **73**, 229–41

[4] C. J. BUSHROD. Note on the Quantitative Implications of Hanawalt's Theory of Corrosion of Magnesium Base Alloys. *J. Inst. Metals* (1947), **73**, 567–72, also discussion p. 825–45.

[5] Report of (A.S.T.M.) Committee B-6 on (the Corrosion of) Die Cast Metals and Alloys. *Proc. A.S.T.M.* (1953), **53**, 227–50.

[6] R. R. ROGERS and W. DINGLEY. The Effect of Small Lead and Silver Additions on the Corrosion-Resistance of Castings of Magnesium and Certain of its Alloys at Elevated Temperature and High Humidity. *Trans. Electrochem. Soc.* (1947), **91**, 693–701.

[7] K. LÖHBERG. The Corrosion of Intermetallic Compounds (of Aluminium and Magnesium), *Z. Metallkunde* (1950), **41**, (2), 56–59.

[8] F. A. FOX and J. K. DAVIES. The Corrosion of Some Magnesium Base Alloys (High and Normal Purity) in Contact with Other Metals. *J. Inst. Metals* (1947), **73**, 553–66.

[9] J. A. PELOUBET. Sea-Air Corrosion of Magnesium Alloys. *Metals and Alloys* (1945), **21**, (5), 1327–33.

[10] L. W. EASTWOOD, F. W. FINK and J. A. DAVIS. The Relative Corrosion Resistance of Magnesium Alloys in Salt Water. *Light Metal Age* (1946), **4**, 16–18, 42.

[11] G. SCHIKORR. On the Relationship of the Atmospheric Corrosion of Metals (including Magnesium) to Sulphur Bearing Impurities in the Air. *Metallo-berflachē* (1947), **1**, (5) 115–16.

[12] A. J. FERKO. Heavy Metal Inserts (in Magnesium and Aluminium Alloys) and Corrosion. *Light Metals* (1947), **10**, (115), 418–21.

[13] G. S. COOK. Corrosion of Metals (including Magnesium) by Insecticidal Solutions. *Corrosion* (1950), **6**, (5), 137–9.

[14] J. F. HAZEL and W. STRERICKER. Effect of Alkaline Detergents on a Magnesium Die-Casting Alloy. *J. Electrochem. Soc.* (1951), **98**, (7), 273–6.

Design and Applications

[1] G. H. FOUND. Efficient Magnesium Castings: Their Design and Production. *Metal Progress* (1949), **56**, (6), 833–40, 892.

[2] G. C. CLOSE. Magnesium Design Principles. *Light Metal Age* (1949), **7**, (5/6), 8–9, 22–23.

[3] J. W. WINKLER. Material in Design-Magnesium Alloys. *Machine Design* (1952), **24**, (10), 141–4.

[4] C. P. J. BALL. Magnesium Progress in Britain. *Light Metals* (1953), **16**, (179), 56–60.

[5] F. EASTWOOD and F. GREEN. Magnesium Alloys in the Textile Industry. *Metal Ind.* (1951), **79**, (6), 103–5, 113.

[6] B. RACLOT. Magnesium in the Textile Industry. *Rev. Aluminium* (1952), (186), 97–100.

[7] C. N. DOUGLAS. Pneumatic Sander (having Cast Magnesium Alloy Parts). *Machine Design* (1949), **21**, (5), 103–6.

[8] ANON. Magnesium Castings for Light Weight Portable Engine Driven Saw. *Product. Eng.* (1946), **17**, (16), 452–4.

[9] E. NEUKIRCH. The Application of Magnesium Alloys in Optical Instruments. *Metall.* (1950), **4**, (7/8), 142–4.

[10] ANON. Die-Cast Magnesium Binoculars. *Met. Ind.* (1954), **84**, (22), 469–71.

[11] A. J. MAROTTA. Magnesium Equipment for an Iron Foundry. *Foundry* (1948), **76**, (2), 208–10, 212, 214.

[12] ANON. Magnesium Tools for Builders. *Modern Metals* (1949), **5**, (3), 37–38.

[13] ANON. Magnesium Wall Forms. *Light Metals* (1950), **13**, (145), 80–83.

[14] F. G. WOOLLARD. (Cast) Magnesium for Cable Drums. *Times Review of Industry* (1950), **4**, (37), 25.

[15] P. LE BIHAN. Lifting Tackle made of Magnesium. *Rev. Aluminium* (1953), (1199), 205–9.

[16] G. BEAUDET. Magnesium Dockboard employs Extruded, Cast and Wrought Parts. *Iron Age* (1951), **167**, (5), 107–9.

[17] ANON. Sound Damping in Business Machines with Magnesium Die-Castings. *Die-Castings* (1950), **8**, (2), 28–30.

[18] G. H. FRIESE-GREENE. Magnesium Furniture justified in Tradition. *Light Metals* (1948), **11**, (124), 236–7, 239–41.

[19] ANON. Eighty-Pound Piano (incorporating Magnesium Alloy Casting. *Modern Metals* (1948), **4**, (2), 40.

[20] ANON. Magnesium Axle Development. *Modern Metals* (1949), **5**, (3), 35.

[21] J. D. HANAWALT and G. K. GLAZA. Magnesium for Automobiles. *Light Metals* (1952), **15**, (175), 324–8; (176), 376–7; (177), 397–8 and (1953), **16**, (178), 11–12.

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